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Gluon TMDs from Quarkonium Production in proton collisions

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in collaboration with J.-P. Lansberg, C. Pisano, F. Scarpa
based on **PLB 784, 217 (2018)** ; **NPB 920, 192 (2017)**

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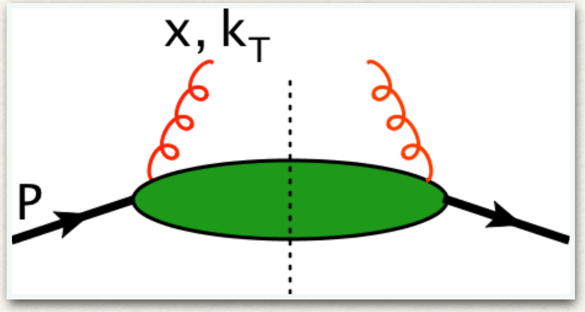

TMD gluonic matrix element

$$\Gamma^{\alpha\beta;\,[\mathcal{W},\mathcal{W}']}(x,k_T) = \int \frac{d\lambda\, d^2 z_T}{(2\pi)^3}\, \mathrm{e}^{ix\lambda + ik_T\cdot z_T}\, \langle P,S|\, F^{n\alpha}(0)\, \mathcal{W}\, F^{n\beta}(\lambda n + z_T)\, \mathcal{W}'\, |P,S\rangle$$

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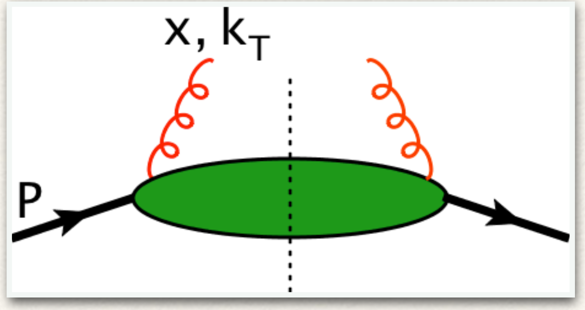

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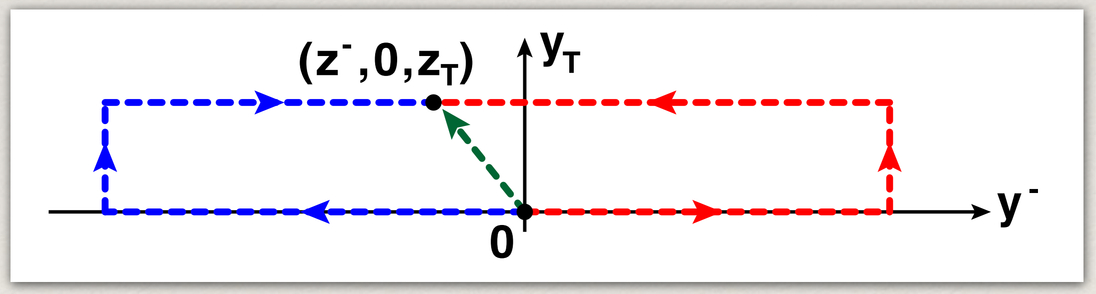
Wilson line in fundamental representation

Color Gauge invariant definition of TMDs ➙ Wilson line

$$\mathcal{W}[a,b] = \mathcal{P} e^{-ig\int_a^b ds\cdot A^a(s)\, t^a}$$

➙ Wilson line for TMD:
nontrivial, process dependent:



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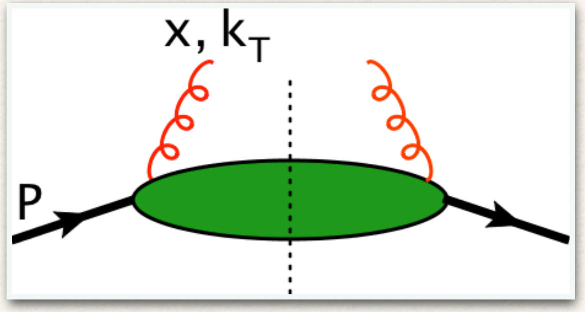

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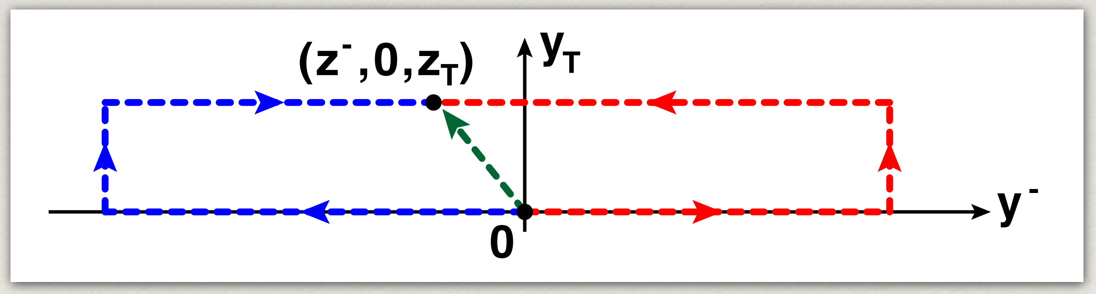

past-pointing WL →
Initial State Interactions:
pp → color singlet + X (DY-type)

$$\Gamma^{\alpha\beta;[-,-]}$$

future-pointing WLs →
Final State Interactions:
ep → jets + X (SIDIS-type)

$$\Gamma^{\alpha\beta;[+,+]}$$

Proper Definition & Soft function

[Collins; Sun, Xiao, Yuan; Aybat, Rogers; see also: Echevarria, Kasemats, Mulders, Pisano, JHEP 07, 158 (2015)]

Inclusion of Soft Function $\Longrightarrow$

$$S(z_T) = \frac{\mathrm{Tr}_c}{N_c} \langle 0| \mathcal{W}_n^\dagger(-z_T/2)\, \mathcal{W}_{\bar{n}}(-z_T/2)\, \mathcal{W}_{\bar{n}}^\dagger(z_T/2)\, \mathcal{W}_n(z_T/2)\,]0\rangle$$

$$\tilde{\Gamma}^{\alpha\beta}(x, b_T) \rightarrow \frac{\tilde{\Gamma}^{\alpha\beta}(x, b_T)}{\sqrt{S(b_T)}}$$

Modification needed in order to have:

1) Renormalizable Matrix Element
2) Finite matching coefficients at small b_T

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Parameterization

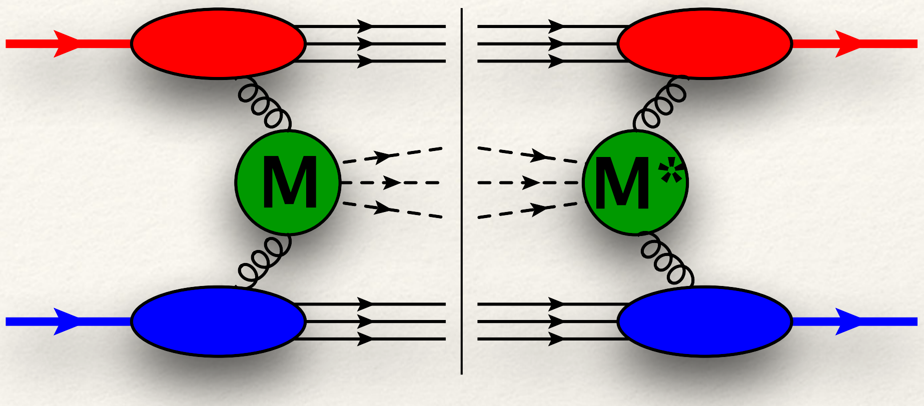
unpolarized & linearly polarized gluons :
helicity flip TMDs ➙ azimuthal modulations

$$\Gamma^{\alpha\beta}(x, k_T) = \frac{1}{2x}\left[-g_T^{\alpha\beta}\ f_1^g(x, k_T^2) + \frac{k_T^\alpha k_T^\beta - \frac{1}{2} k_T^2 g_T^{\alpha\beta}}{M^2}\ h_1^{\perp g}(x, k_T^2) \right]$$

Gluon TMDs from pp - collisions

[J.-P. Lansberg, C. Pisano, M.S., NPB 920, 192 (2017)]

General TMD expression for gluon fusion:



$$\frac{d\sigma}{d^4q\ldots}(q_T \ll Q) \propto \mathcal{C}[\Gamma^{\alpha\alpha'}(x_a, k_{aT})\,\Gamma^{\beta\beta'}(x_b, k_{bT})]\ (\mathcal{M}_{\alpha\beta}\,(\mathcal{M}_{\alpha'\beta'})^*)$$

$$\mathcal{C}[w\,f\,g] = \int d^2k_{aT} \int d^2k_{bT}\,\delta^{(2)}(k_{aT} + k_{bT} - q_T)\,w(k_{aT}, k_{bT})\,f(x_a, k_{aT})\,g(x_b, k_{bT})$$

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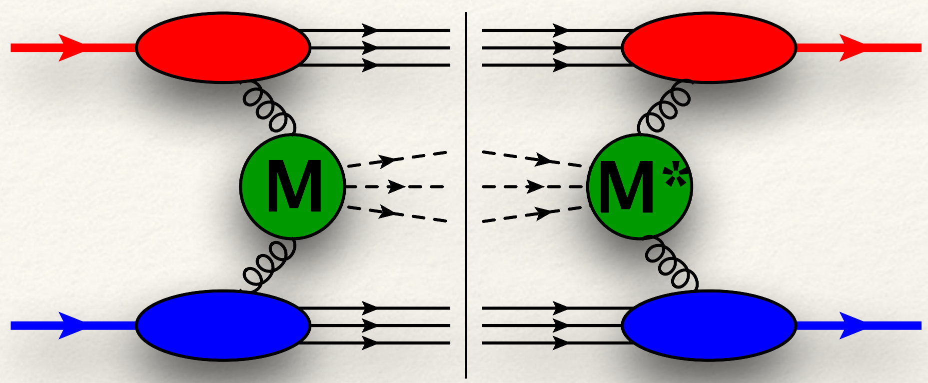

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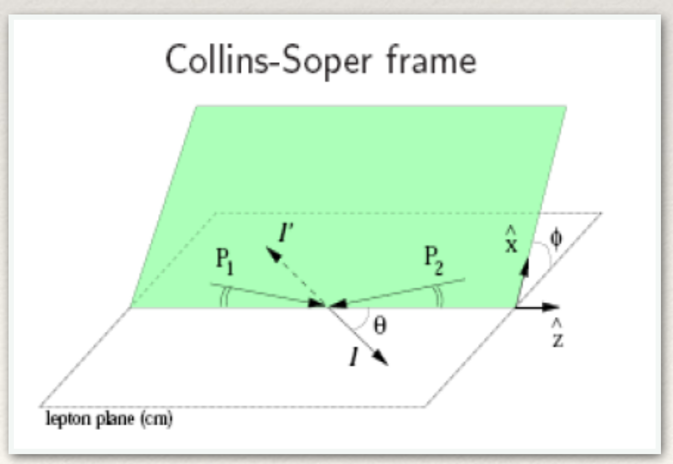
2-particle (pair) final states in pp - collisions

$$\frac{d\sigma^{gg}}{d^4q\; d\Omega}\Big|_{q_T \ll Q} = \hat{F}_1\; [f_1^g \otimes f_1^g] + \hat{F}_2\; [h_1^{\perp g} \otimes h_1^{\perp g}] + \cos(2\phi)\hat{F}_3\; [h_1^{\perp g} \otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi)\hat{F}_4\; [h_1^{\perp g} \otimes h_1^{\perp g}]$$



Evaluate cross section in c.m. frame of the produced pair

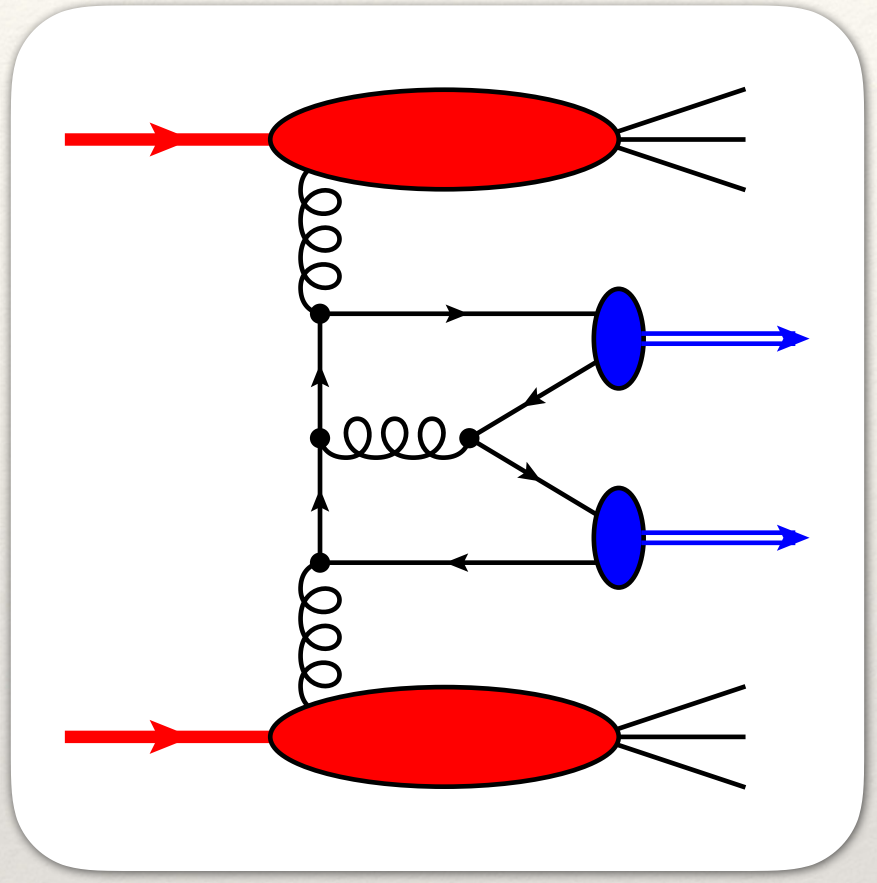
Collins - Soper angles θ , ϕ

Gluon TMDs do not appear in Drell-Yan

Double J/ψ(ϒ)- production

[Lansberg, Pisano, Scarpa, PLB 784, 217 (2018)]

TMD - formalism: J/ψ pair back-to-back; Color singlet



Here: Sample diagram (of about O(40))

Full analytical LO amplitude

$$g + g \to J/\psi + J/\psi$$

(J/ψ in color singlet configuration)

Presented in Appendix of
[Qiao, Sun, Sun; 0903.0954] (Kudos!)

Helicity formalism: contract with polarization vectors
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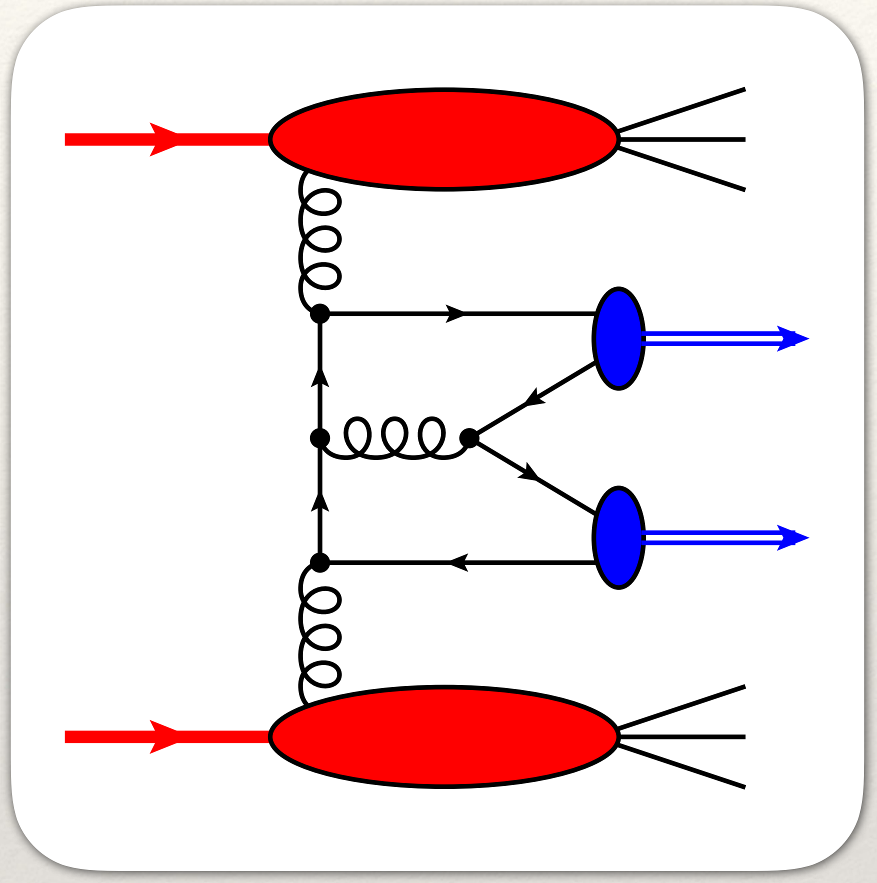

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$$F_i(Q, \cos^2\theta) \propto \frac{\sum_{k=0}^{N_i} c_k(\alpha)\,(\cos^2\theta)^k}{(1-(1-\alpha^2)\cos^2\theta)^4}$$

Degree of polynomial $N_i = 6,\ 4,\ 5,\ 6$

Q: invariant mass of Quarkonium pair

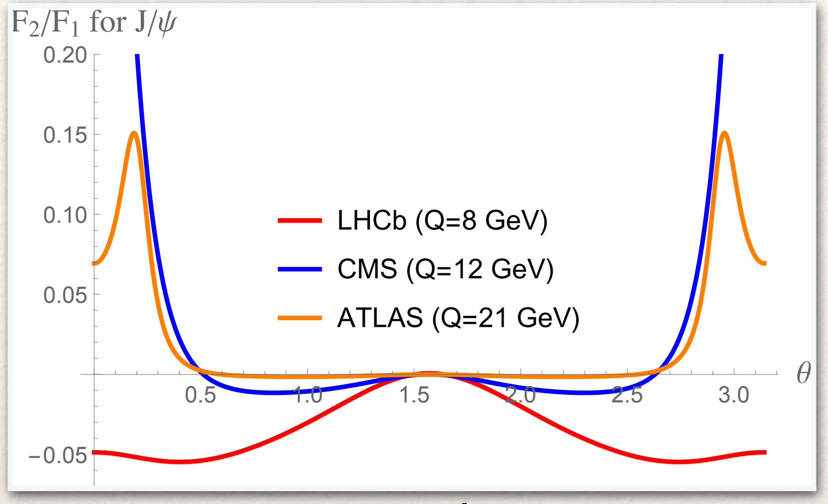
$$\alpha = \frac{2M_{J/\psi}}{Q}$$

$\alpha = 1$ threshold limit

$\alpha = 0$ high-energy limit

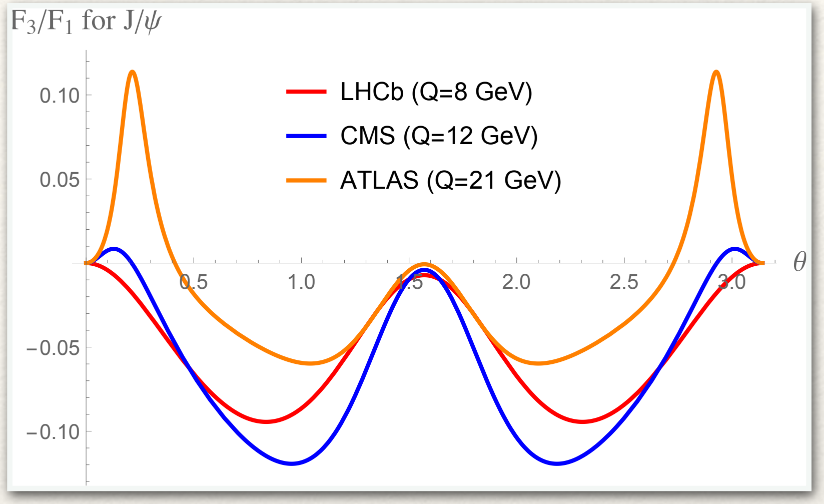
$$\left.\frac{d\sigma^{gg}}{d^4q\; d\Omega}\right|_{q_T\ll Q} = \hat{F}_1\,[f_1^g\otimes f_1^g] + \hat{F}_2\,[h_1^{\perp g}\otimes h_1^{\perp g}] + \cos(2\phi)\hat{F}_3\,[h_1^{\perp g}\otimes f_1^g + f_1^g\otimes h_1^{\perp g}] + \cos(4\phi)\hat{F}_4\,[h_1^{\perp g}\otimes h_1^{\perp g}]$$

Ratios:



q_T - spectrum:

Modification from lin. pol. glue mostly negligible



cos(2ϕ):

about -10% at θ = π/4, 3π/4

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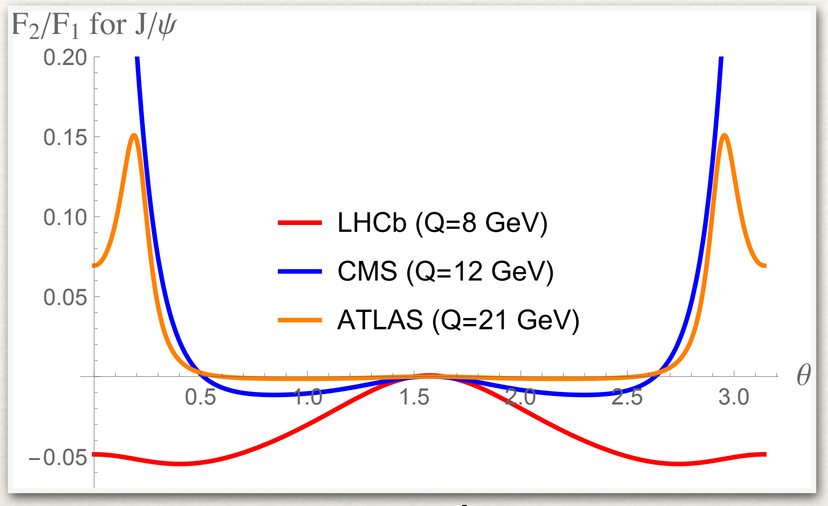

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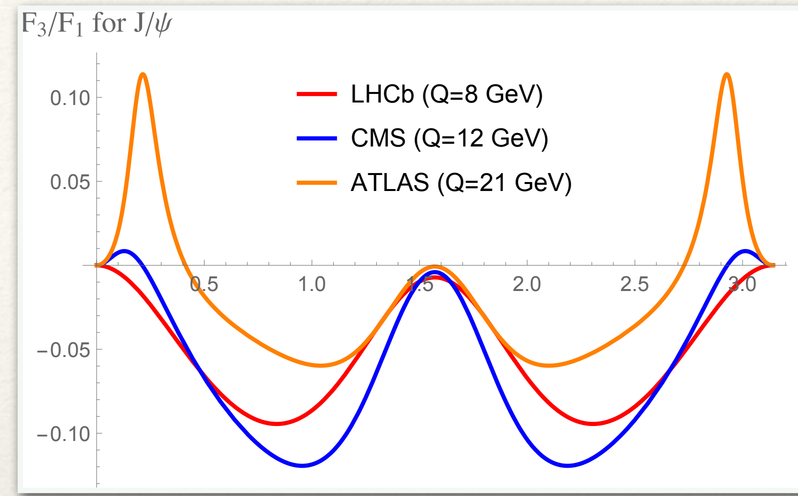

cos(2ϕ):

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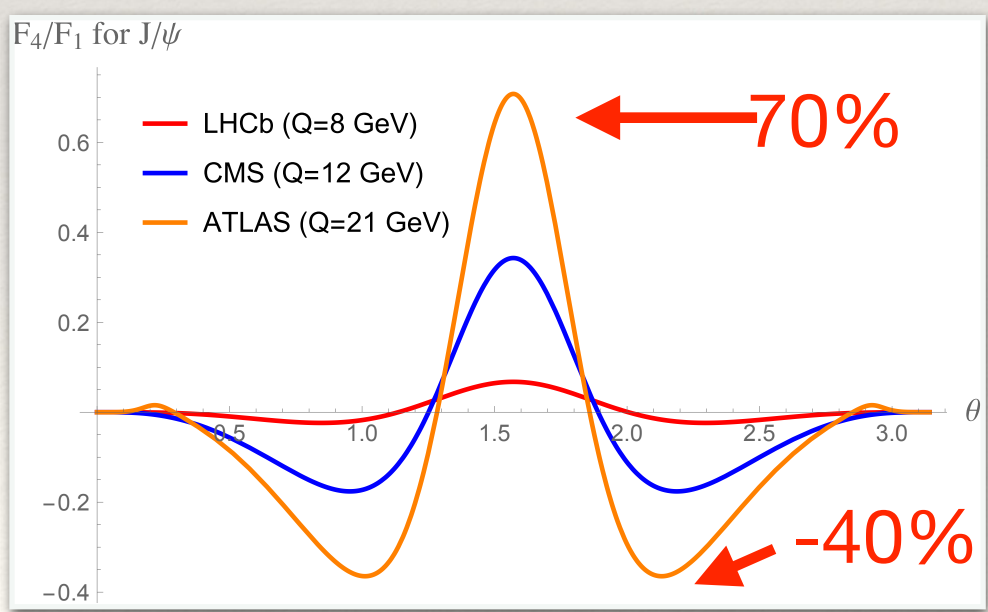
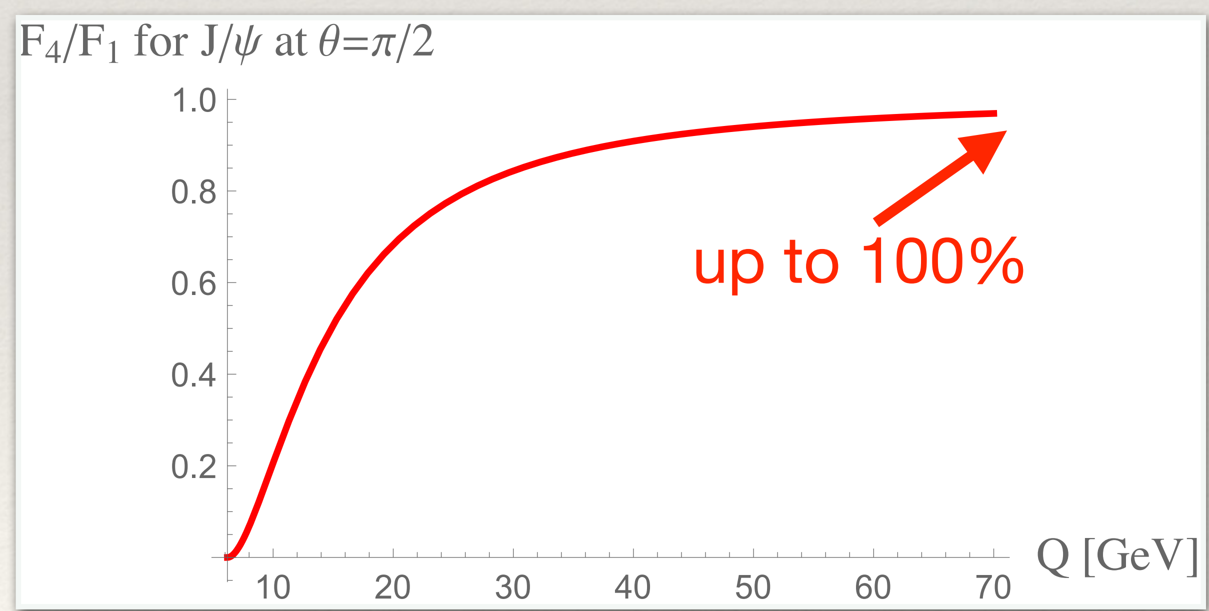
cos(4ϕ): Large at θ = π/2!





$$F_4(\theta = \tfrac{\pi}{2}, Q \gg 2M_{J/\psi}) \rightarrow F_1$$

unique to this process!

q_T - spectrum: Data on J/ψ – pairs available from LHC

Measurements from CMS and ATLAS at 7,8 TeV, but not suitable for TMD exploration

LHCb data (2017) at 13 TeV slightly above threshold, Q = 8 GeV

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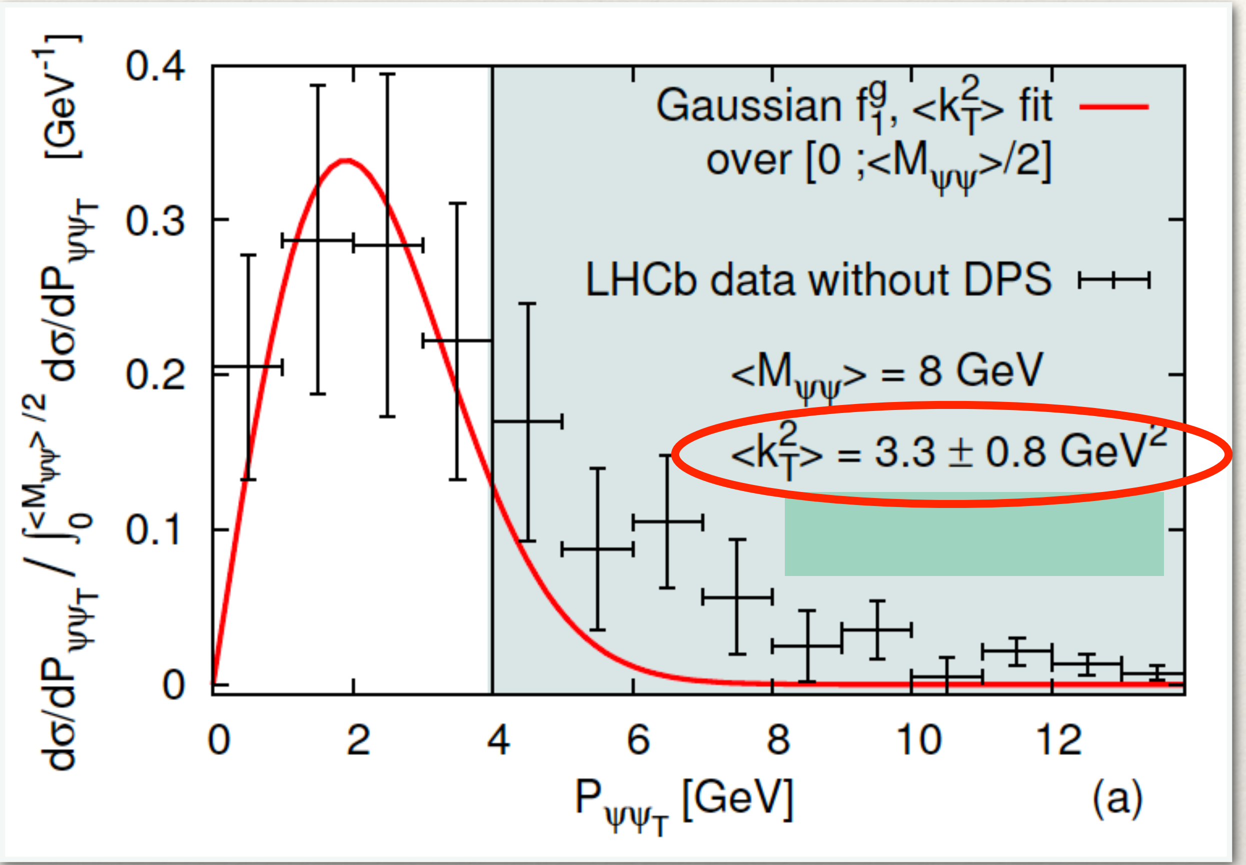

Fit observable

$$\frac{\left[\frac{d\sigma}{dq_T}\right]_{\text{bins}}}{\int_0^{Q/2} dq_T \left[\frac{d\sigma}{dq_T}\right]_{\text{bins}}} \propto \frac{\mathcal{C}[f_1^g\, f_1^g]}{\int_0^{Q/2} dq_T\, \mathcal{C}[f_1^g\, f_1^g]}$$

First glimpse on unpol. gluon TMD:

No fits for f_1 so far, Gaussian ansatz

$$f_1^g(x, k_T^2; Q = 8\,\text{GeV}) = \frac{g(x)}{\pi \langle k_T^2 \rangle} \exp\left(-k_T^2/\langle k_T^2 \rangle\right)$$

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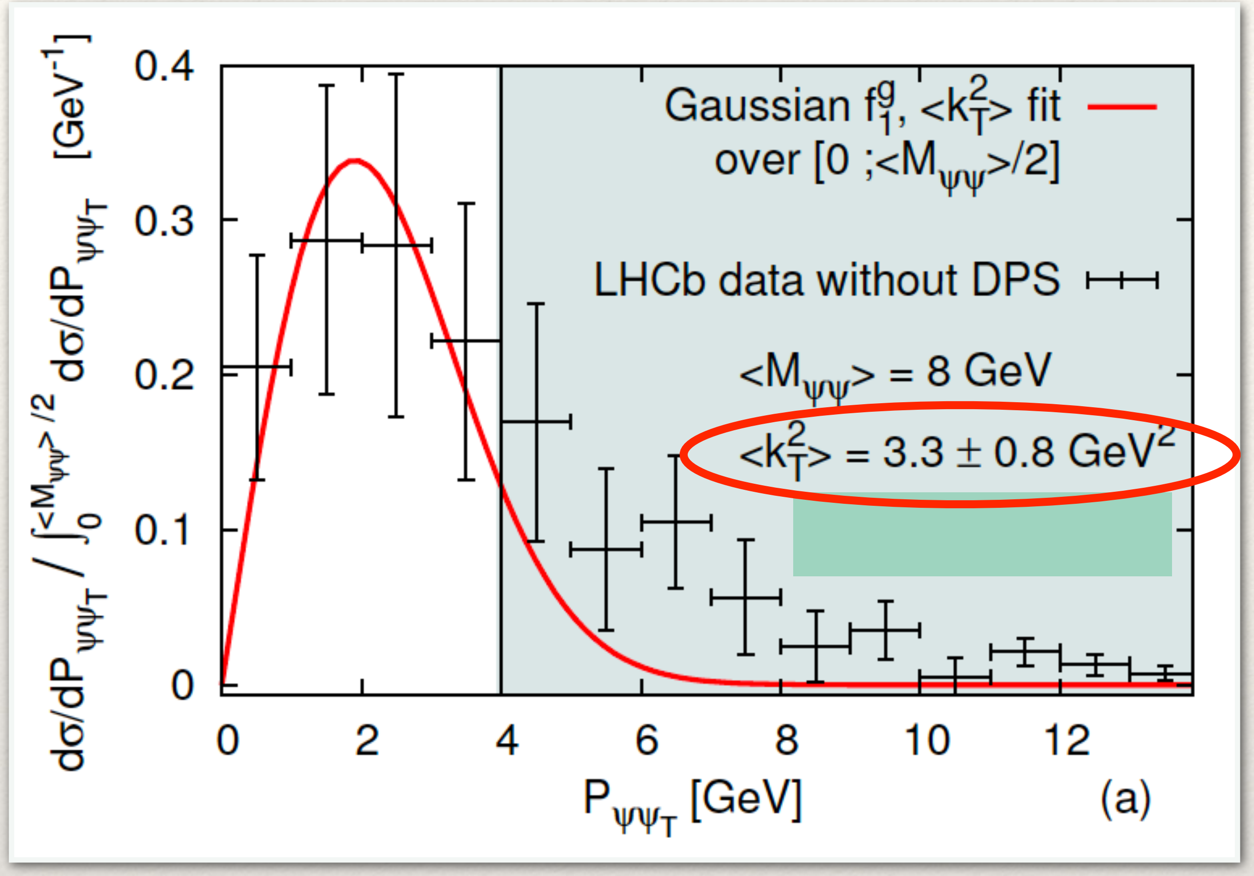

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- One-parameter fit for $<k_T^2>$, χ^2 = 1.08: *effective*, but not *intrinsic* width
- TMD evolution not included, needed if more data sets at different Q are available
- LHCb data corrected for double-parton scattering
- Expectation: Color Singlet Mode dominant

[Lansberg, Shao, PLB 2015; Ko, Yu, Lee, JHEP 2011; Li, Xu, Liu, Zhang, JHEP 1023]

Azimuthal modulation: no data available → predictions

Suggested observables: weighted cross section ratios

$$\frac{\int d\phi \cos(2\phi) \left[\frac{d\sigma\, d\phi}{dq_T}\right]_{\text{bins}}}{\int_0^{Q/2} dq_T \left[\frac{d\sigma}{dq_T}\right]_{\text{bins}}} \propto \frac{\mathcal{C}[w_3\, h_1^{\perp g}\, f_1^g] + \mathcal{C}[w_3\, f_1^g\, h_1^{\perp g}]}{\int_0^{Q/2} dq_T\, \mathcal{C}[f_1^g\, f_1^g]}$$

$$\frac{\int d\phi \cos(4\phi) \left[\frac{d\sigma\, d\phi}{dq_T}\right]_{\text{bins}}}{\int_0^{Q/2} dq_T \left[\frac{d\sigma}{dq_T}\right]_{\text{bins}}} \propto \frac{\mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}]}{\int_0^{Q/2} dq_T\, \mathcal{C}[f_1^g\, f_1^g]}$$

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Input for linearly pol. gluon TMD: models

Model 1

$$h_1^{\perp g}(x, k_T^2) = \frac{M^2}{\langle k_T^2\rangle} \frac{g(x)}{\pi \langle k_T^2\rangle} \exp\left(1 - \frac{3\, k_T^2}{2\langle k_T^2\rangle}\right)$$

Model 2: Saturation of positivity bound

$$h_1^{\perp g}(x, k_T^2) = \frac{2M^2}{k_T^2}\, f_1^g(x, k_T^2)$$

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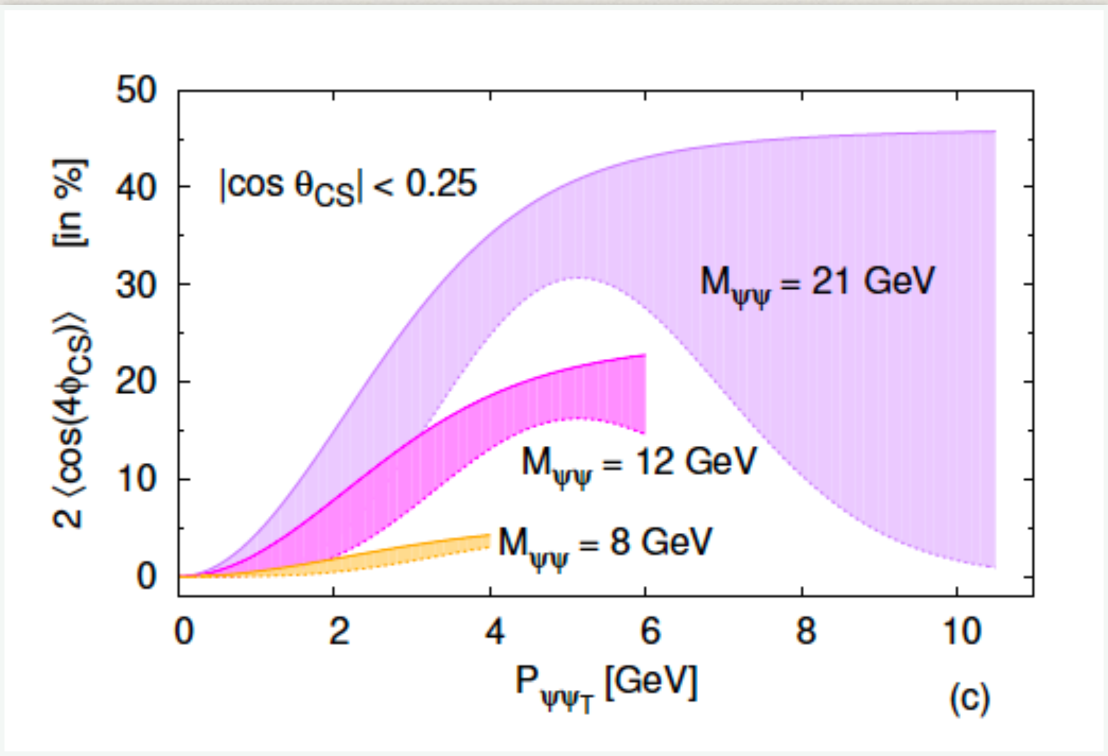
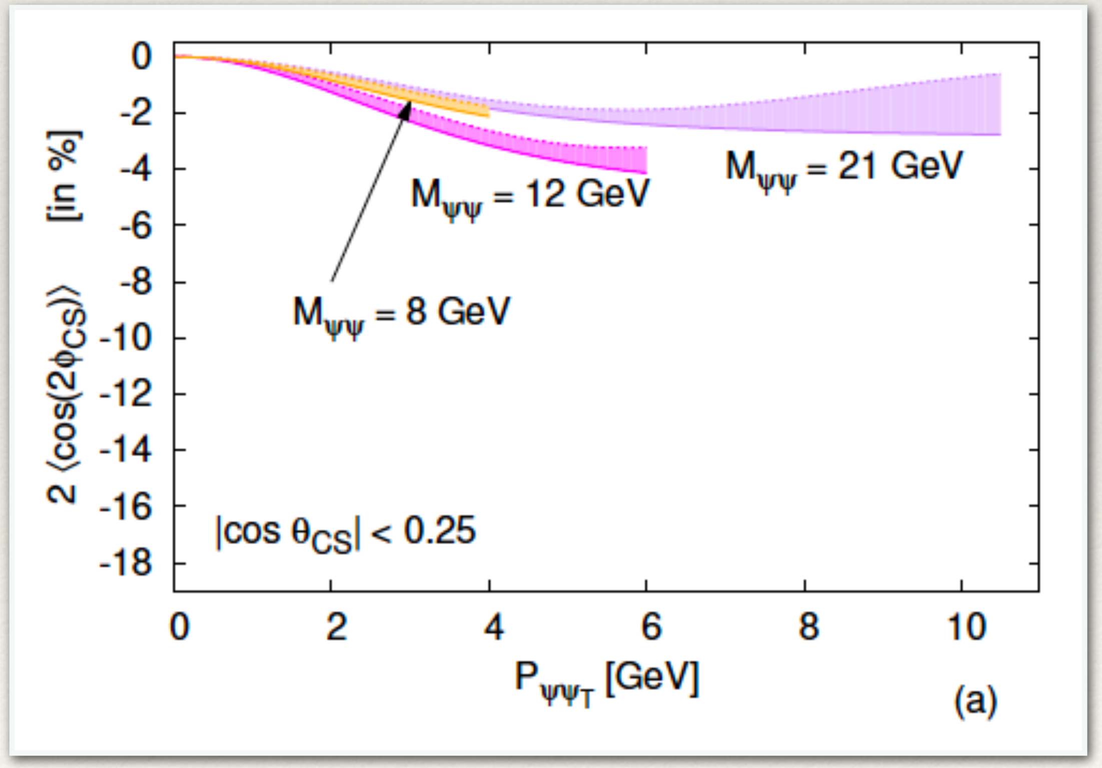




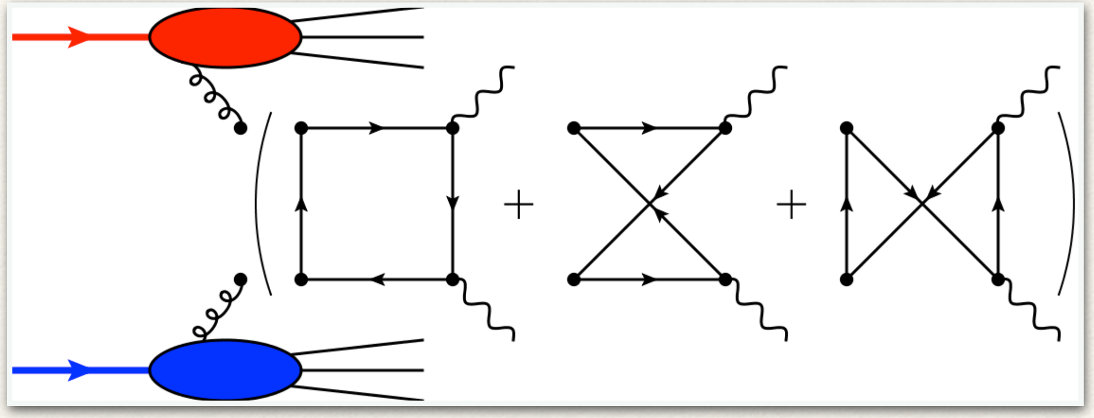
- Large effects for cos(4φ) for Q larger than threshold: 10% - 20%, cos(2φ) few percent

Summary & Outlook

- Gluon TMDs ➙ new aspects on the 3D gluonic structure of the nucleon ➙ linear gluon polarization
- Several final states in pp - collisions: Leptons, Photons, Heavy Quarkonium states
- Promising: J/ψ pairs at the LHC, particularly large: $\cos(4\phi)$ azimuthal modulation
- Data is coming: first extraction of unpolarized gluon TMD
- Important for EIC: An idea what to expect for gluon TMDs
- Outlook:
  - Improve fit for unpolarized gluon TMD including ATLAS, CMS data and TMD evolution
  - Extend helicity formalism to spin-dependent observables and gluon TMDs (sPHENIX)

Diphoton production

[Qiu, M.S., Vogelsang, PRL 2011]



- contaminations from quark contributions:
  only cos(4ϕ)-modulation purely gluonic

- Photons are difficult to measure:
  $\gamma\gamma$ - production: background from π^0 - decays

Linearly polarized gluons potentially useful for Higgs - production

[Boer, den Dunnen, Pisano, MS, Vogelsang, PRL 2012, 2013]

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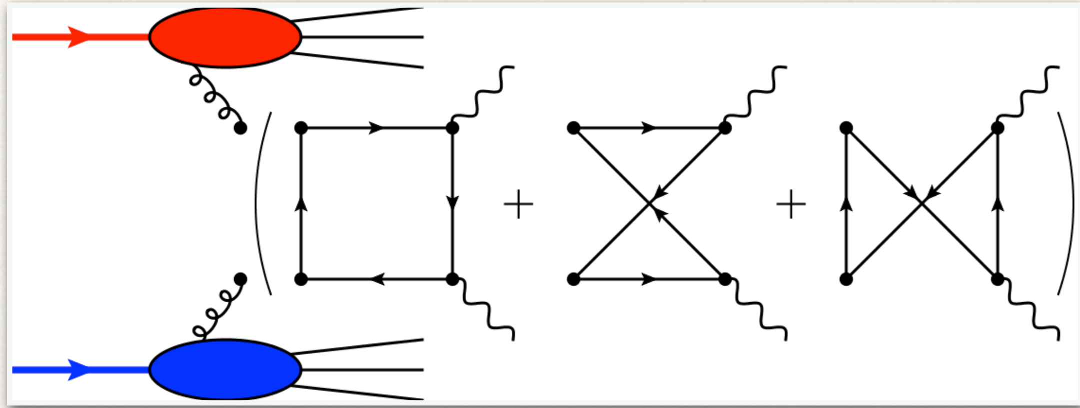

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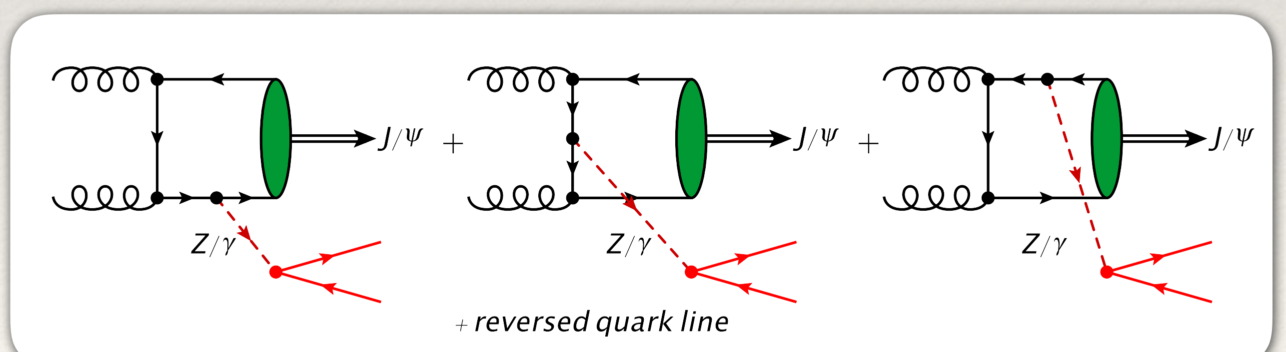
Associated $\Upsilon(J/\psi)$ + γ/Z- production at the LHC

[den Dunnen, Lansberg, Pisano, M.S., PRL 2014 / Lansberg, Pisano, M.S., NPB 2017]

Quarkonium in color singlet configuration compatible with TMD factorization

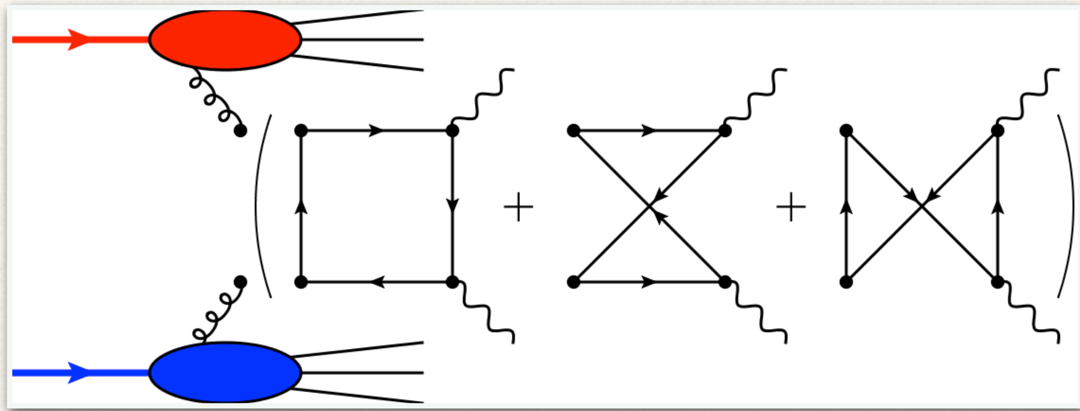


- main contribution from gluon fusion
- Υ - production: Color Octet (Fragm.)≪ Color Singlet ✔
- Real γ: $F_2 = 0$, $\cos(2\phi) \sim 3\%$, $\cos(4\phi) \sim 1\%$!
- Real Z: $F_1 >> F_2, F_3, F_4$

first glimpse of linearly polarized gluons may be possible at the LHC

Diphoton production

[Qiu, M.S., Vogelsang, PRL 2011]



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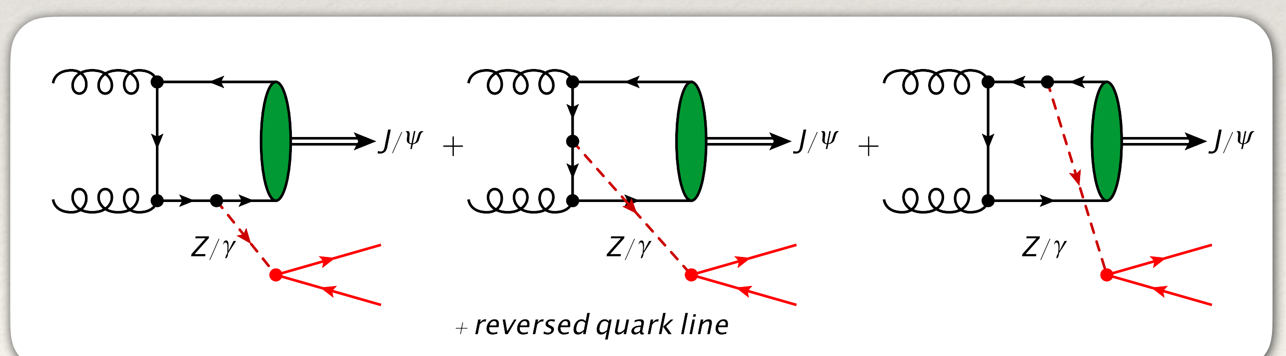
[den Dunnen, Lansberg, Pisano, M.S., PRL 2014 / Lansberg, Pisano, M.S., NPB 2017]

Quarkonium in color singlet configuration compatible with TMD factorization



- main contribution from gluon fusion
- ϒ - production:
  Color Octet (Fragm.)« Color Singlet ✔
- Real γ: $F_2 = 0$, cos(2ϕ) ~ 3%, cos(4ϕ) ~ 1%!
- Real Z: $F_1 >> F_2, F_3, F_4$

first glimpse of linearly polarized gluons may be possible at the LHC

Processes sensitive to gluon TMDs

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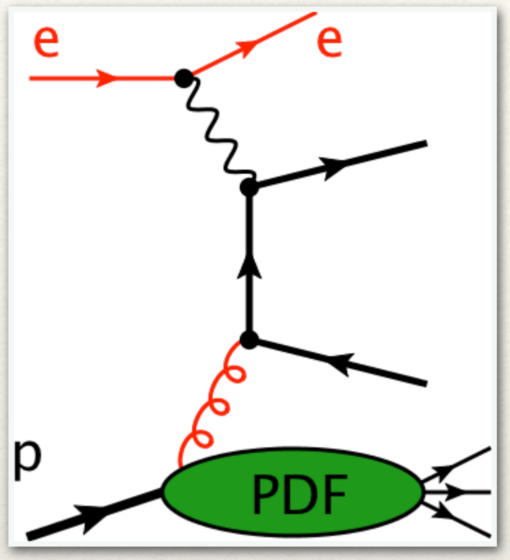


Heavy Quark production in e + p - collisions

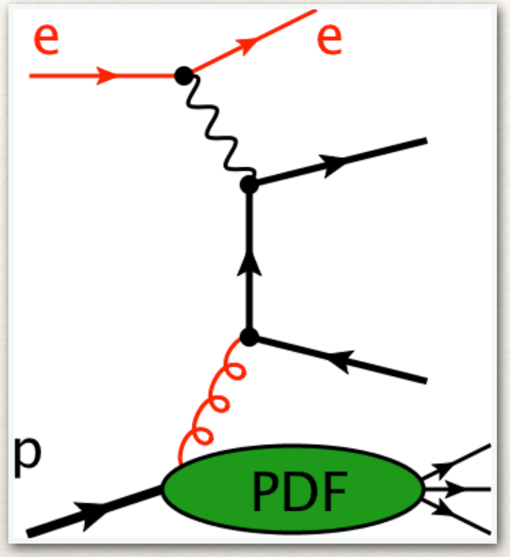
[Boer, Brodsky, Mulders, Pisano, PRL 2011]

$$e + p^{(\uparrow)} \rightarrow e' + \mathrm{jet}(c, b) + \mathrm{jet}(\bar{c}, \bar{b}) + X$$

TMD factorization ok!

Spin dependent (+independent...) gluon TMDs: EIC would be ideal!

Processes sensitive to gluon TMDs



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Spin dependent (+independent...) gluon TMDs: EIC would be ideal!

unpolarized cross section: $$\frac{d\sigma_{UU}}{dq_T} \propto \Big(F_1 + F_2 \cos(2\phi)\Big)$$

azimuthally independent term: $F_1 \propto f_1^g(x, q_T)$ ➝ unpol. gluon distribution

azimuthally dependent term: $F_2 \propto h_1^{\perp g}(x, q_T)$ ➝ linearly pol. gluons