GHP meeting, April 12, 2019, Denver

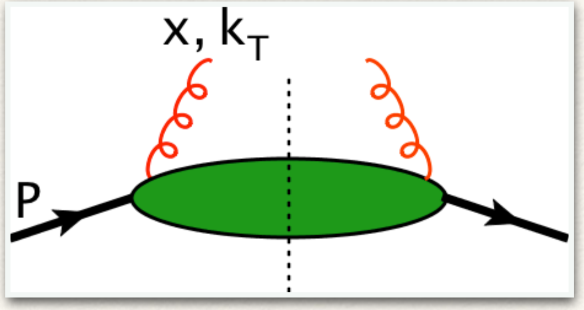
Gluon TMDs from Quarkonium Production in proton collisions

Marc Schlegel
Department of Physics
New Mexico State University

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

Gluon TMDs = Transverse Momentum Dependent Parton Distributions of gluons in nucleon

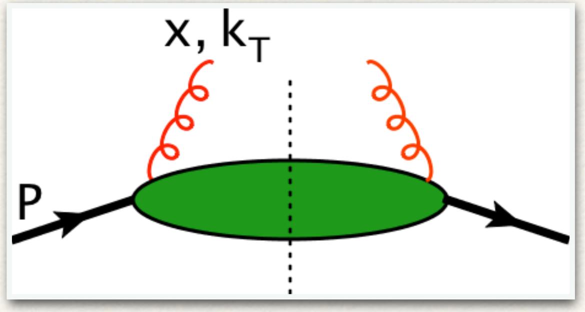
Gluon TMDs = Transverse Momentum Dependent Parton Distributions of gluons in nucleon



TMD gluonic matrix element

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

Gluon TMDs = Transverse Momentum Dependent Parton Distributions of gluons in nucleon



TMD gluonic matrix element

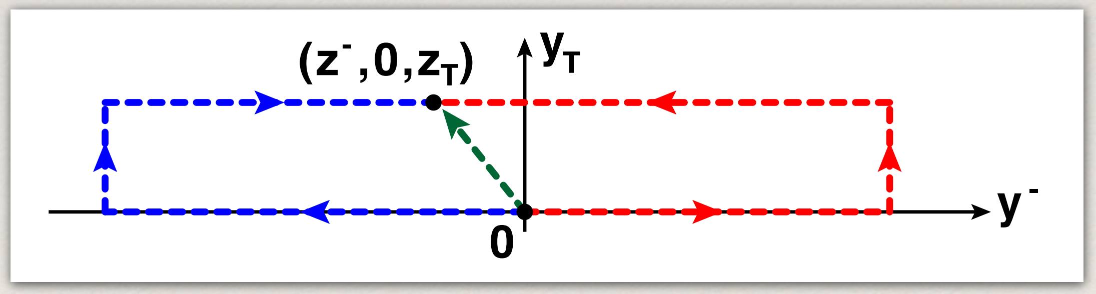
$$\Gamma^{\alpha\beta;\,[\mathcal{W},\mathcal{W}']}(x,k_T) = \int \frac{d\lambda d^2 z_T}{(2\pi)^3}\, \mathrm{e}^{ix\lambda + ik_T\cdot z_T}\, \langle P,S|\, F^{n\alpha}(0)\, \mathcal{W}\, F^{n\beta}(\lambda n + z_T)\, \mathcal{W}'\, |P,S\rangle$$

Wilson line in fundamental representation

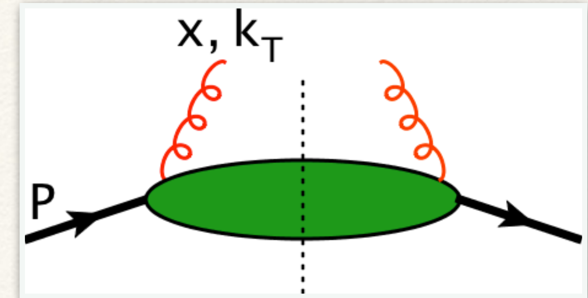
Color Gauge invariant definition of TMDs ➙ Wilson line

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

➙ Wilson line for TMD:
nontrivial, process dependent:



Gluon TMDs = Transverse Momentum Dependent Parton Distributions of gluons in nucleon



TMD gluonic matrix element

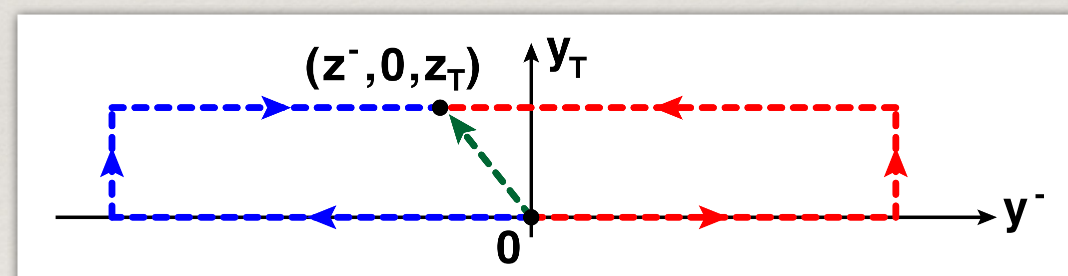
$$\Gamma^{\alpha\beta;\,[\mathcal{W},\mathcal{W}']}(x, k_T) = \int \frac{d\lambda d^2 z_T}{(2\pi)^3}\, \mathrm{e}^{ix\lambda + ik_T\cdot z_T}\, \langle P, S|\, F^{n\alpha}(0)\, \mathcal{W}\, F^{n\beta}(\lambda n + z_T)\, \mathcal{W}'\, |P, S\rangle$$

Wilson line in fundamental representation

Color Gauge invariant definition of TMDs ➙ Wilson line

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

➙ Wilson line for TMD:
nontrivial, process dependent:



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 $\Longrightarrow$

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

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

Modification needed in order to have:

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

Proper Definition & Soft function

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

Inclusion of Soft Function $\Longrightarrow$

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

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

Modification needed in order to have:

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

Parameterization

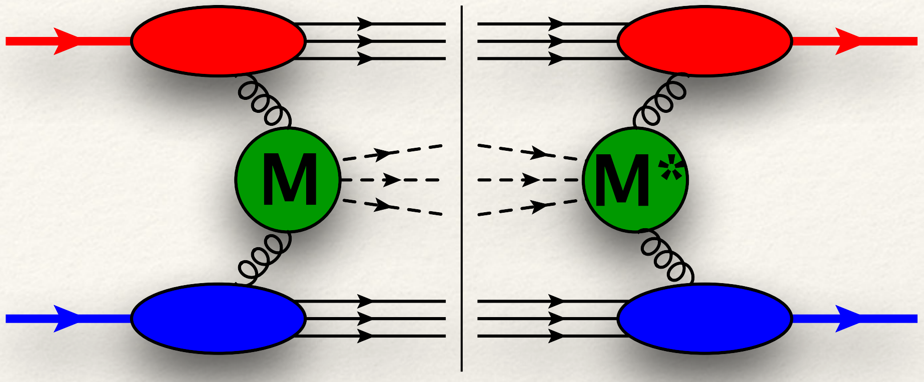
unpolarized & linearly polarized gluons :
helicity flip TMDs ➙ azimuthal modulations

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

Gluon TMDs from pp - collisions

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

General TMD expression for gluon fusion:

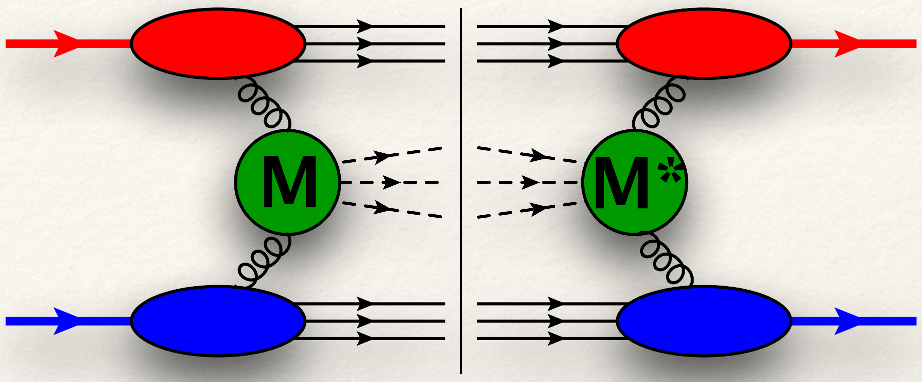


$$\frac{d\sigma}{d^4q\ldots}(q_T \ll Q) \propto \mathcal{C}[\Gamma^{\alpha\alpha'}(x_a, k_{aT})\,\Gamma^{\beta\beta'}(x_b, k_{bT})]\;(\mathcal{M}_{\alpha\beta}\,(\mathcal{M}_{\alpha'\beta'})^*)$$

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

Gluon TMDs from pp - collisions

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



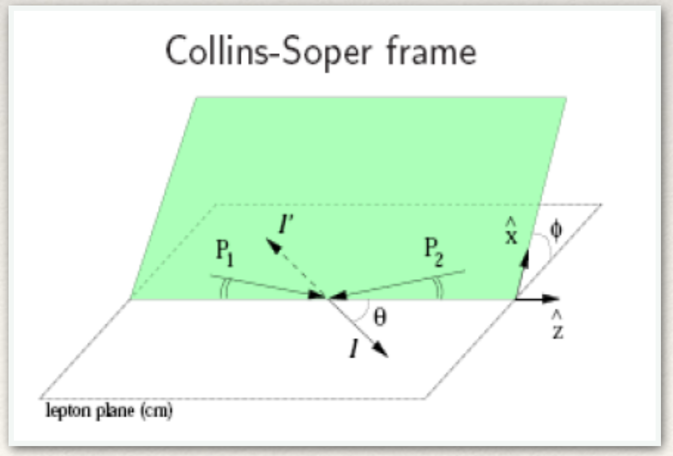
General TMD expression for gluon fusion:

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

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

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

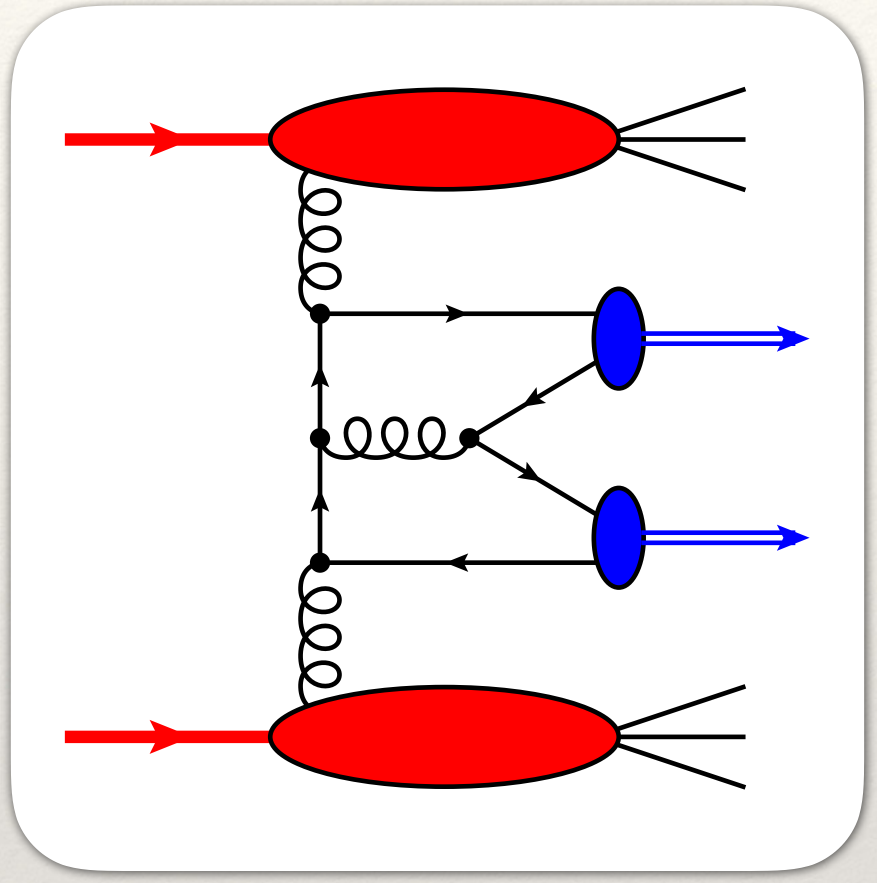
Collins - Soper angles θ , ϕ

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)

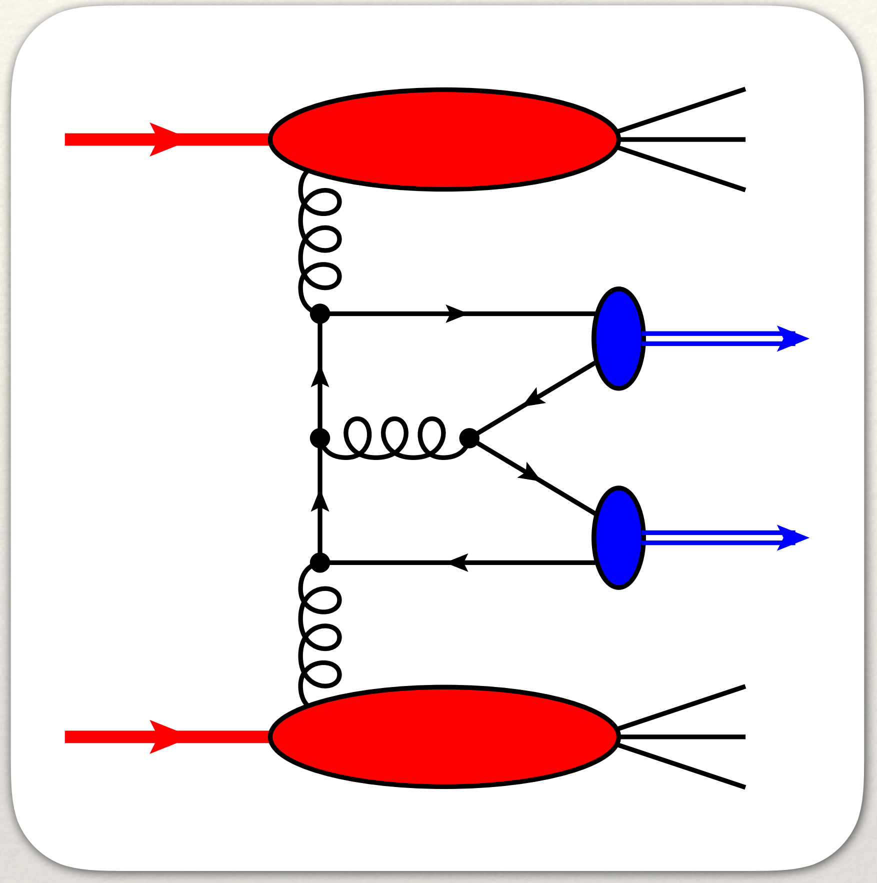
Presented in Appendix of
[Qiao, Sun, Sun; 0903.0954] (Kudos!)

Helicity formalism: contract with polarization vectors
→ perturbative factors F_1, F_2, F_3, F_4

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

→ perturbative factors F_1, F_2, F_3, F_4

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

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

Q: invariant mass of Quarkonium pair

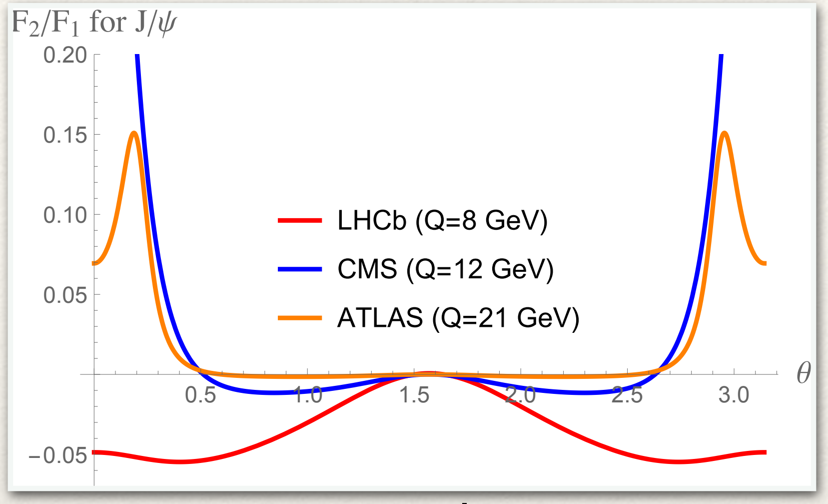
$$\alpha = \frac{2M_{J/\psi}}{Q}$$

$\alpha = 1$ threshold limit

$\alpha = 0$ high-energy limit

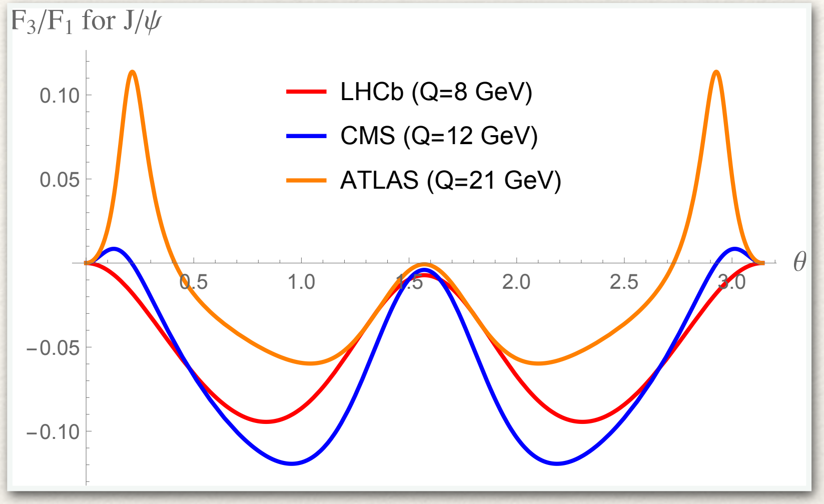
$$\frac{d\sigma^{gg}}{d^4q\; d\Omega}\Big|_{q_T \ll Q} = \hat{F}_1\; [f_1^g \otimes f_1^g] + \hat{F}_2\; [h_1^{\perp g} \otimes h_1^{\perp g}] + \cos(2\phi)\hat{F}_3\; [h_1^{\perp g} \otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi)\hat{F}_4\; [h_1^{\perp g} \otimes h_1^{\perp g}]$$

Ratios:



q_T - spectrum:

Modification from lin. pol. glue mostly negligible

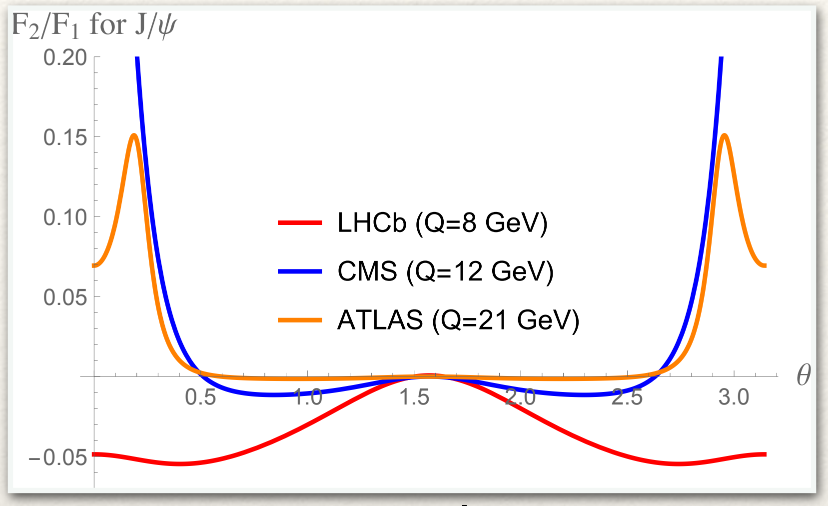


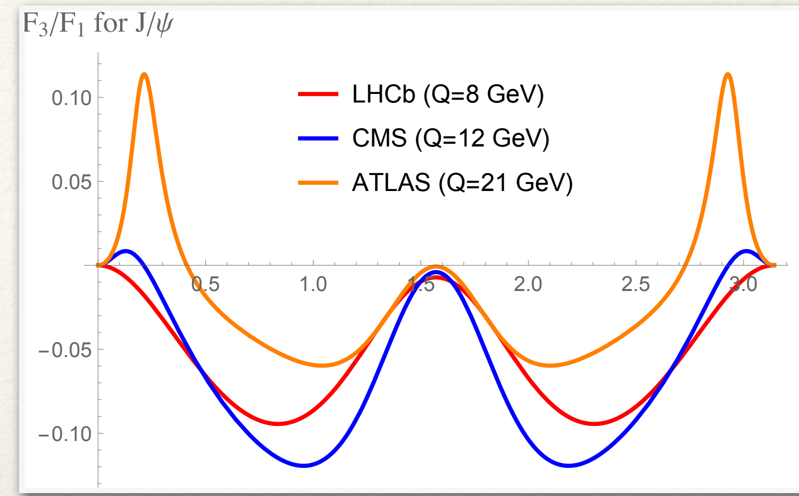
cos(2ϕ):

about -10% at $\theta = \pi/4,\ 3\pi/4$

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

Ratios:





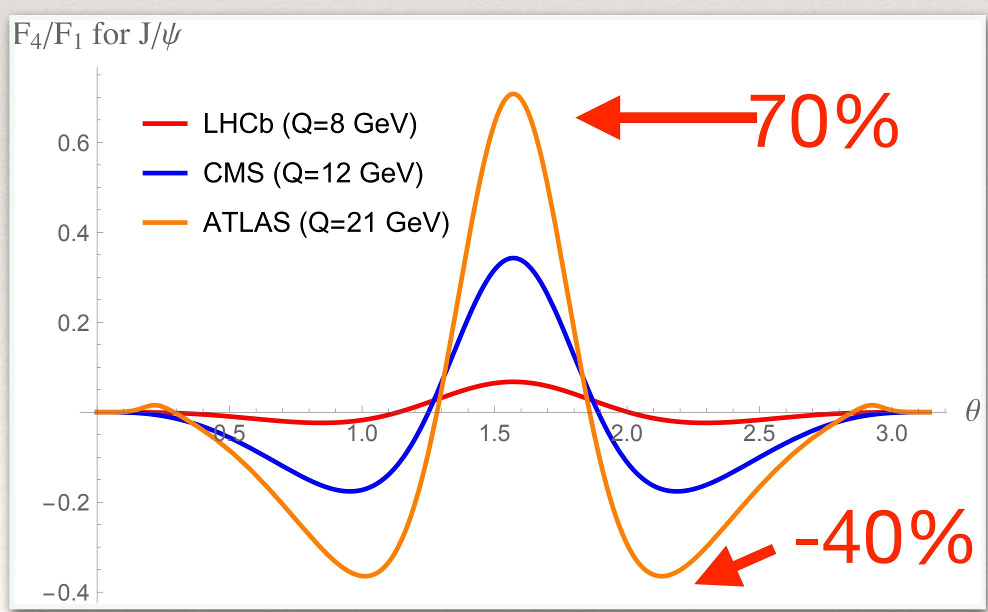
q_T - spectrum:

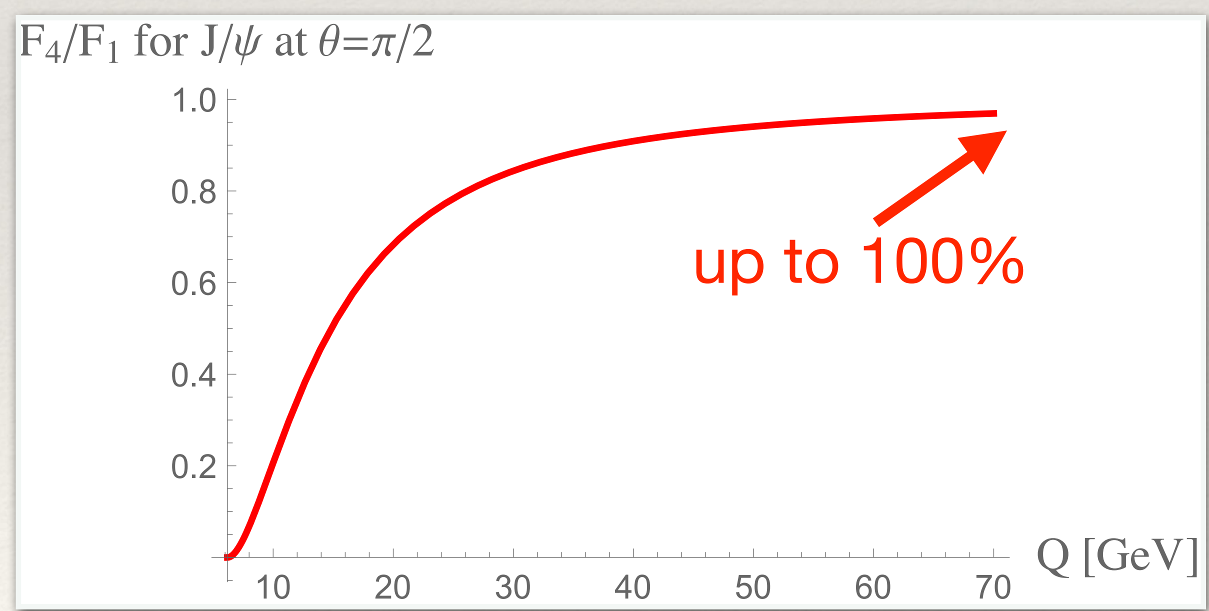
Modification from lin. pol. glue mostly negligible

cos(2ϕ):

about -10% at θ = π/4, 3π/4

cos(4ϕ): Large at θ = π/2!





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

unique to this process!

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

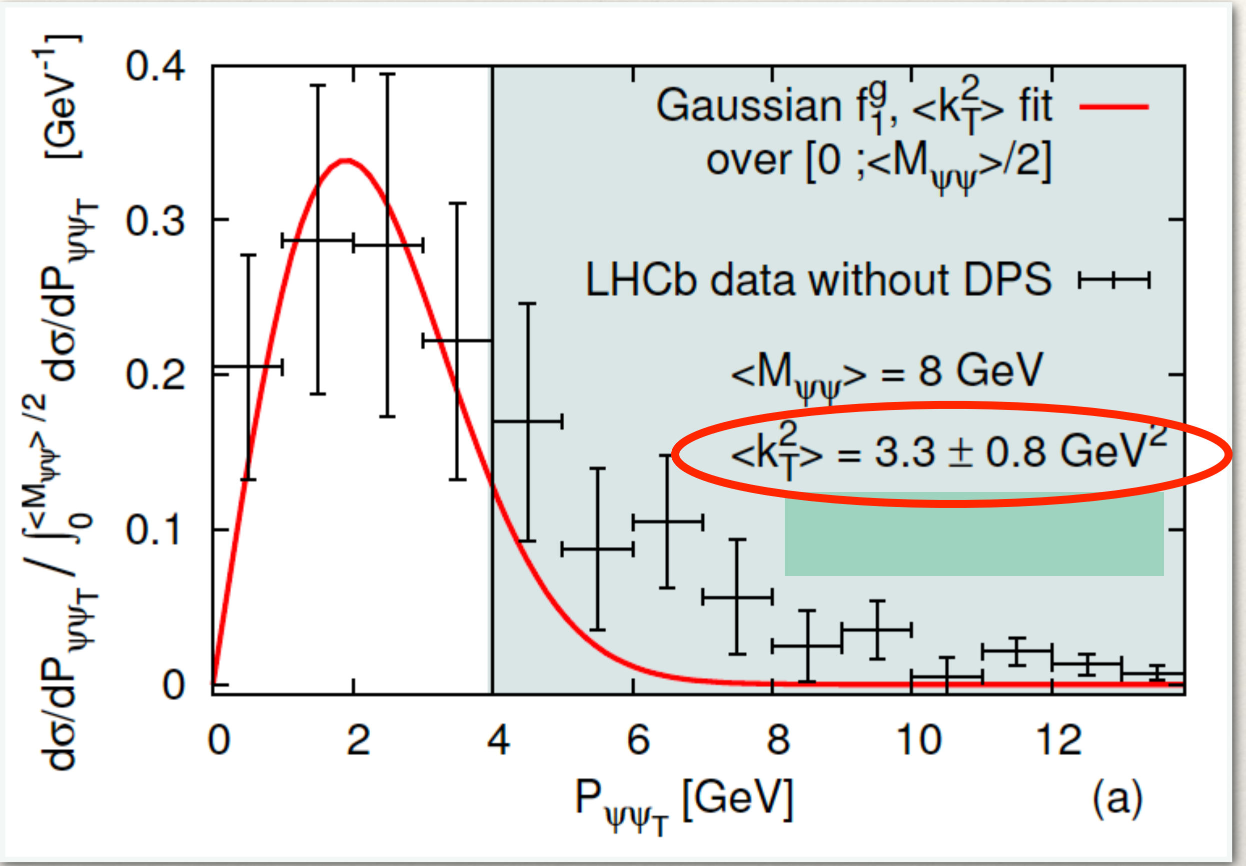
Measurements from CMS and ATLAS at 7,8 TeV, but not suitable for TMD exploration

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

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



Fit observable

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

First glimpse on unpol. gluon TMD:

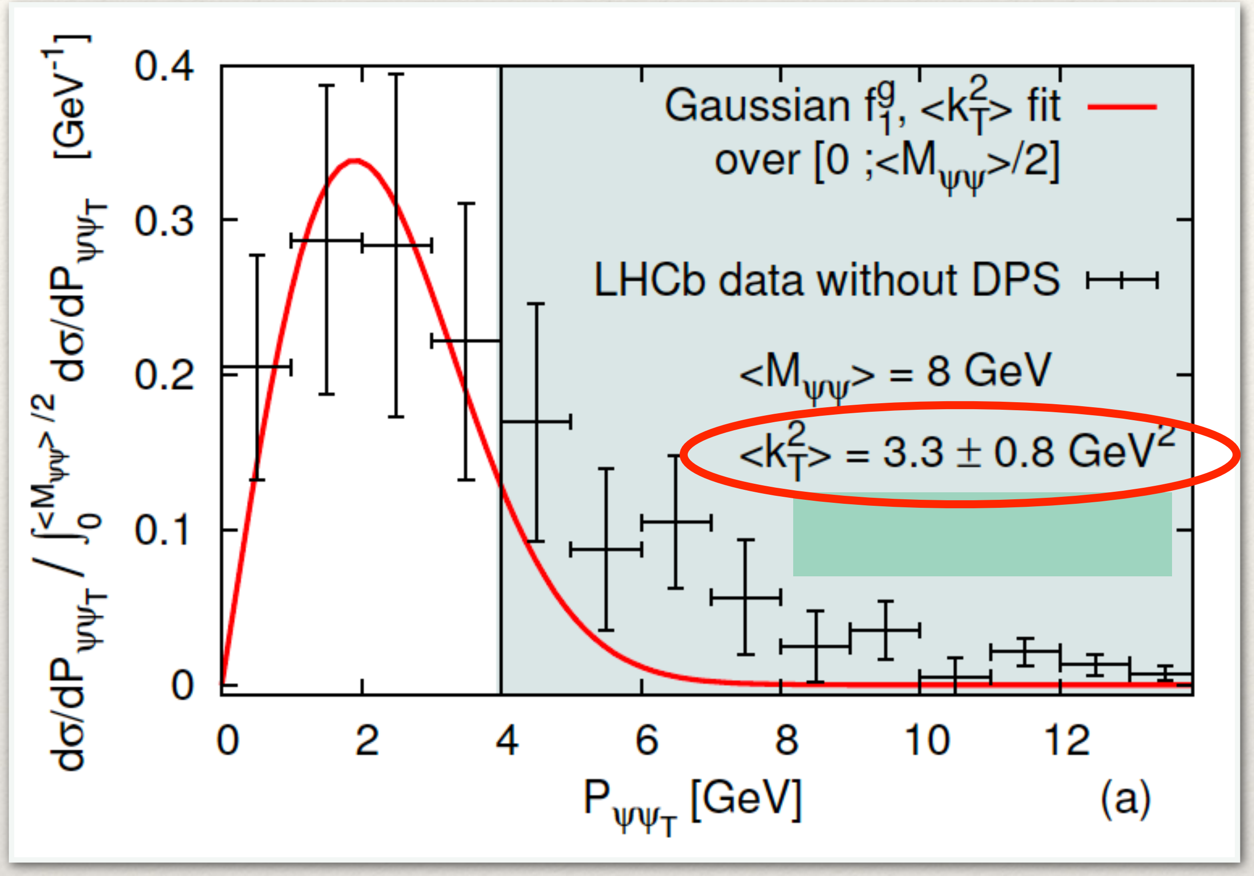
No fits for f_1 so far, Gaussian ansatz

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

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



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

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

- One-parameter fit for $\langle k_T^2\rangle$, 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

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

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

Azimuthal modulation: no data available → predictions

Suggested observables: weighted cross section ratios

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

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

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

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

Azimuthal modulation: no data available → predictions

Suggested observables: weighted cross section ratios

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

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

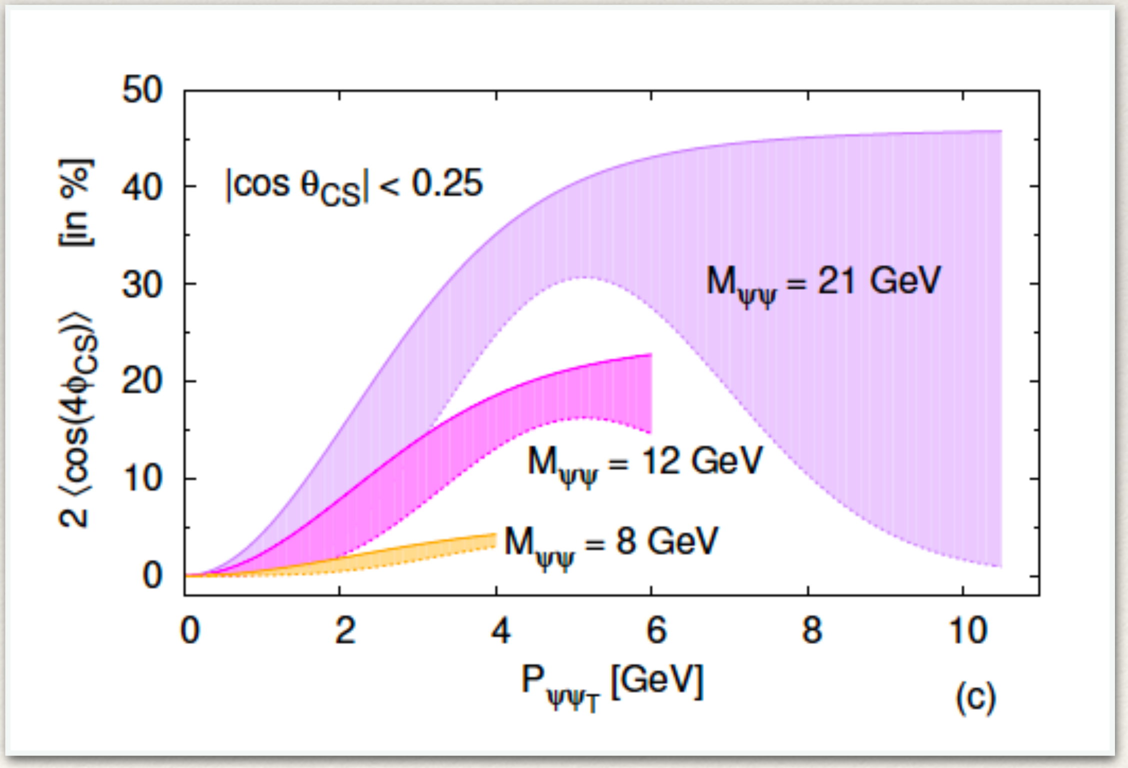
Input for linearly pol. gluon TMD: models

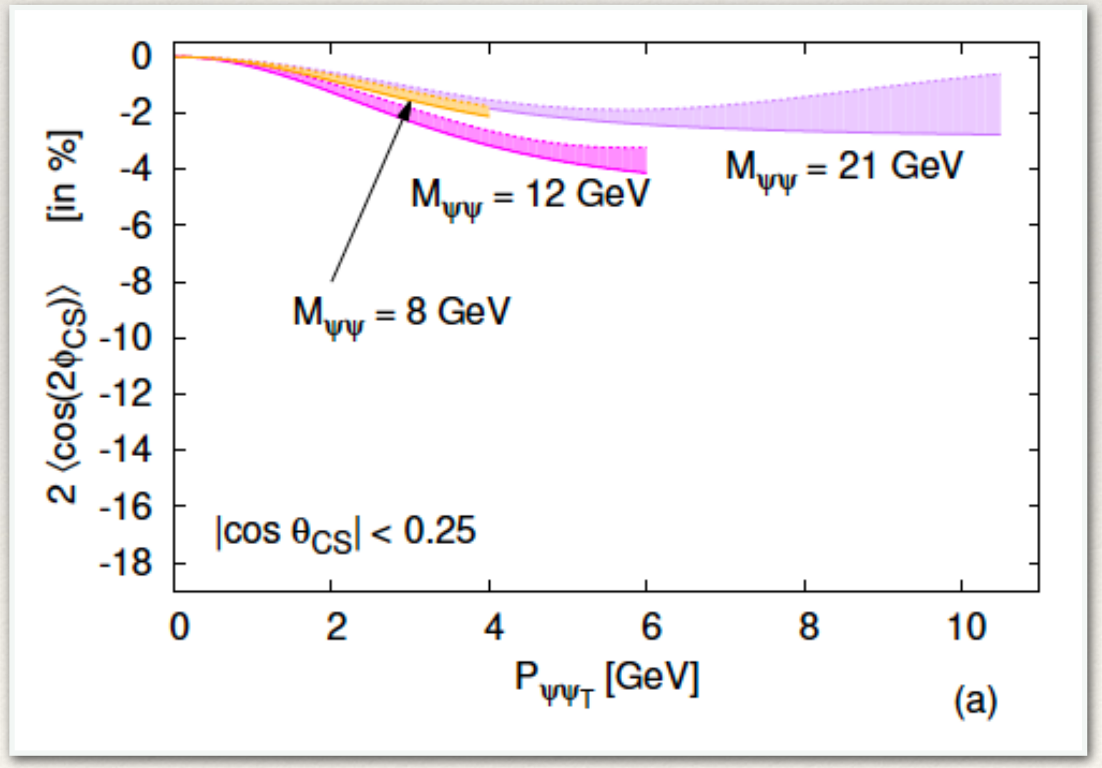
Model 1

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

Model 2: Saturation of positivity bound

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





- 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)