Linearly Polarized Gluon TMD

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Transverse Momentum Dependent (TMD) Factorization

Problem:

Description of q_T - distributions in collinear factorization at $q_T \ll Q$

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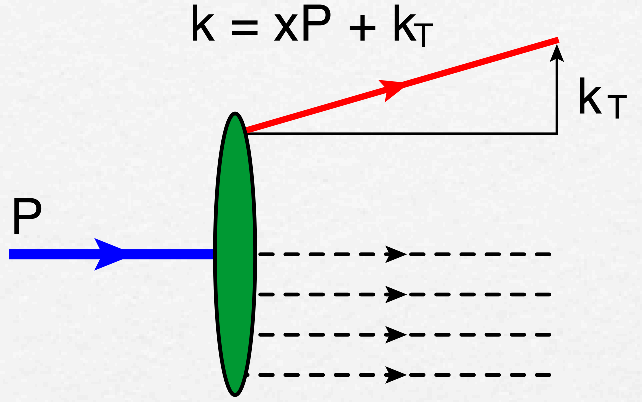
Idea of TMD factorization:

small transverse momentum q_T from

"intrinsic" transverse parton momentum k_T

→ different kind of factorization

→ additional degree of freedom of partonic motion



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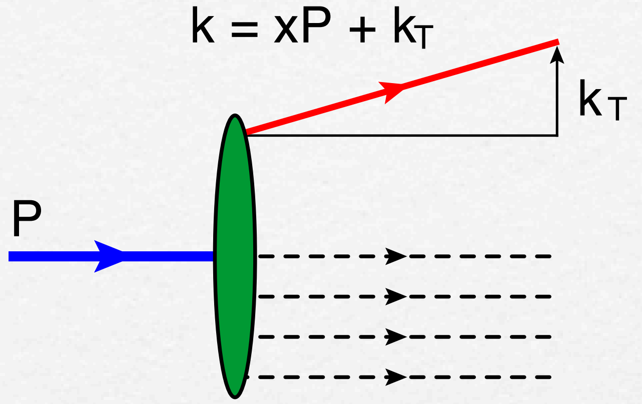

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→ different kind of factorization

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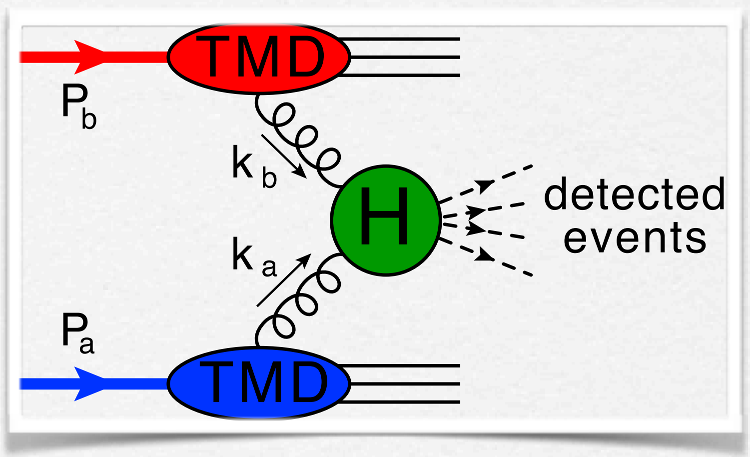
- ☐ TMD factorization theorem

  (gluon-gluon) $\quad q_T \ll Q$



$$d\sigma \propto \mathrm{dPS}\,|H|^2 \int d^2k_{aT} \int d^2k_{bT}\; \delta^{(2)}(k_{aT}+k_{bT}-q_T)\;\Gamma(x_a,k_{aT})\;\Gamma(x_b,k_{bT}) \;+\mathcal{O}(q_T/Q)$$

$$= \Gamma_a \otimes \Gamma_b \;=\; C[\Gamma_a\;\Gamma_b]$$

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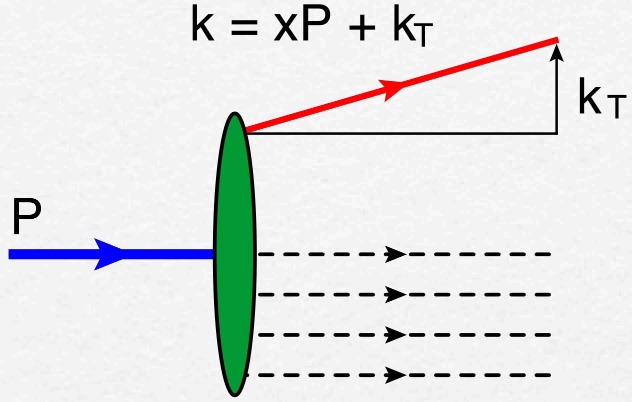

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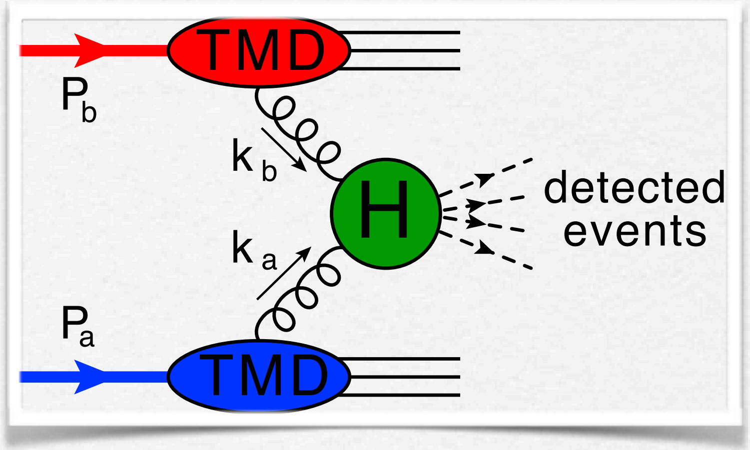

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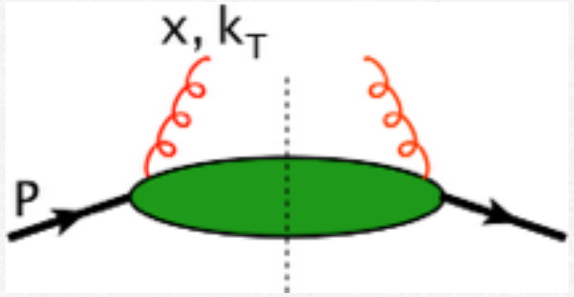
$$= \Gamma_a \otimes \Gamma_b \; = \; C[\Gamma_a \; \Gamma_b]$$

- valid for pp - collisions with color singlet final states

[Collins; Ji, Ma, Yuan; Qiu; Rogers, Mulders; ...]

TMD gluonic matrix element



$$\Gamma^{\alpha\beta}(x, k_T) = \frac{1}{x^2(P\cdot n)} \int \frac{d\lambda\ d^2 z_T}{(2\pi)^3}\ \mathrm{e}^{i\lambda x(P\cdot n)+ik_T\cdot z_T} \langle P|F^{n\alpha}(0)\ \mathcal{W}\ F^{n\beta}(\lambda n + z_T)|P\rangle$$

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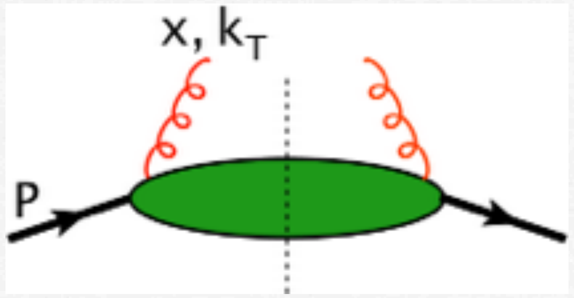

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Parameterization:

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

f_1^g → TMD distribution of unpolarized gluons

$h_1^{\perp g}$ → TMD distribution of linearly polarized gluons

[Mulders, Rodrigues]

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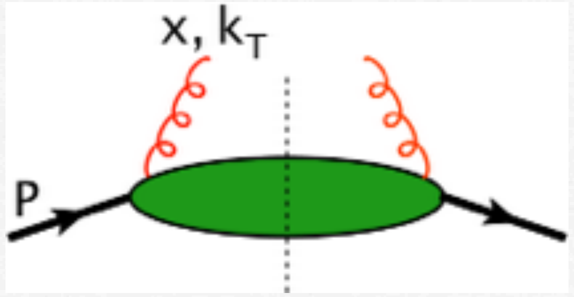

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$h_1^{\perp g}$ → TMD distribution of linearly polarized gluons

[Mulders, Rodrigues]

- both TMD distributions essentially unknown
- $h_1^{\perp g}$ prop. to transverse momentum k_T, absent in coll. factorization
- $h_1^{\perp g}$ causes gluon helicity flip (non-pert.) → azimuthal modulations

Linearly Polarized Gluons

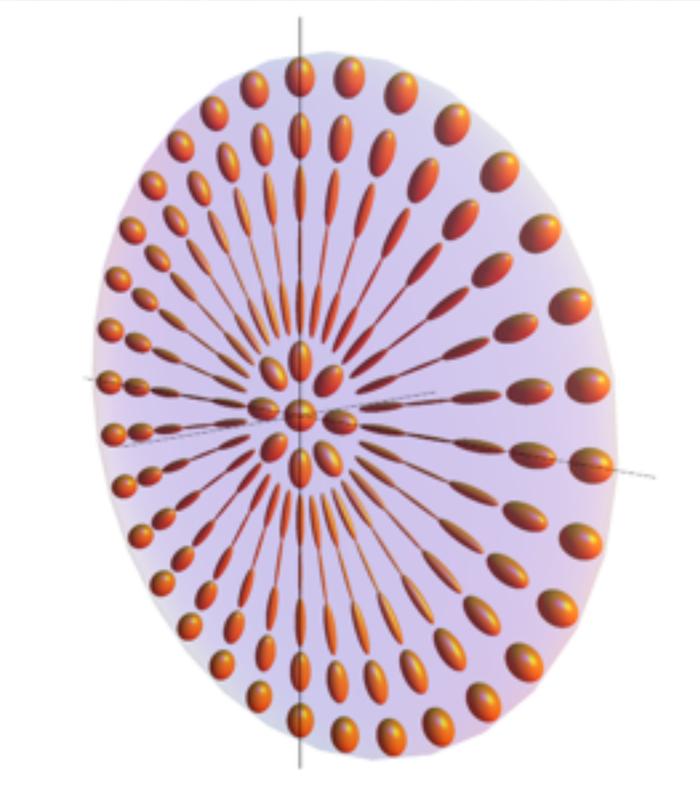
- positivity bound $-h_1^{\perp g} \leq \frac{2M^2}{k_T^2} f_1^g \leq h_1^{\perp g}$

  [Mulders, Rodrigues]

  positivity bound often (partially) saturated in models (pert., Color Glass Condensate)

- linear polarization in transverse plane

$h_1^{\perp g} > 0$



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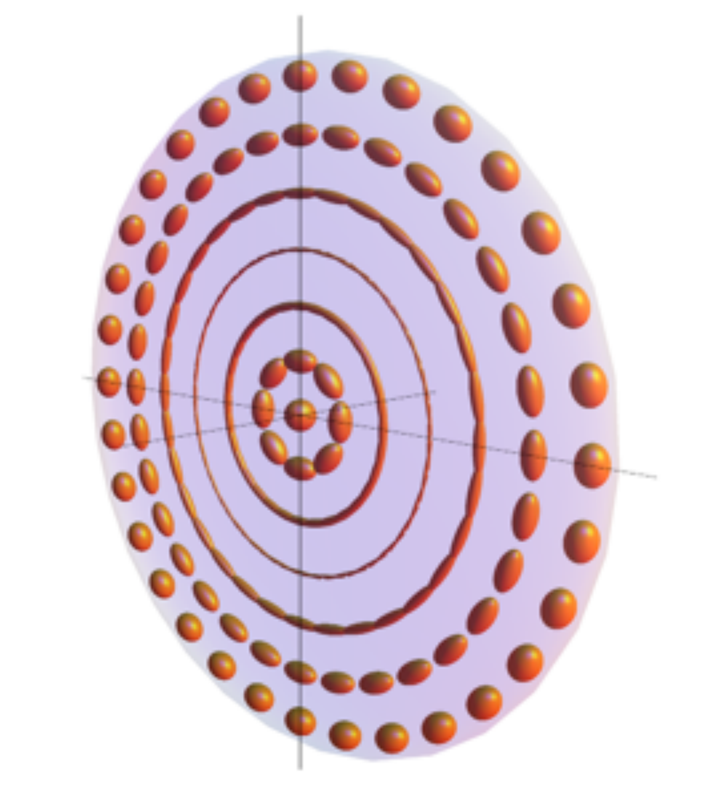


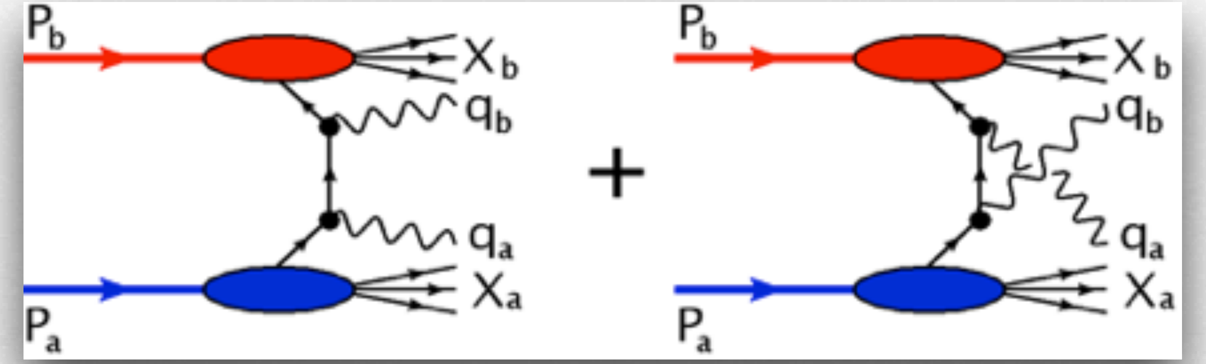
- both gluon distributions fundamental properties of the nucleon structure!

Gluon TMDs
from
pp - collisions
at the LHC

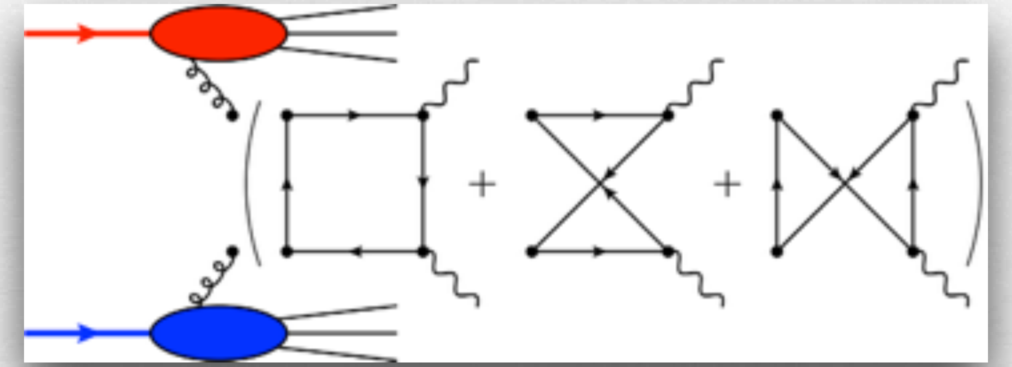
Photon Pair production

[Qiu, M.S., Vogelsang, PRL 107, 062001 (2011)]

quark TMDs



gluon TMDs at $O(\alpha_s^2)$



$$\frac{d\sigma^{gg}}{d^4q\, d\Omega} \propto \left(\frac{\alpha_s}{2\pi}\right)^2 \left(F_1[f_1^g \otimes f_1^g] + F_2[h_1^{\perp g} \otimes h_1^{\perp g}] + \cos(2\phi) F_3[h_1^{\perp g} \otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi) F_4[h_1^{\perp g} \otimes h_1^{\perp g}]\right)$$

- no colored final state ($\gamma\gamma$, γZ, ZZ) ⇒ TMD factorization ok
- contaminations from quark contributions:
  only F_4 - structure [cos(4ϕ)-modulation] purely gluonic
- $\gamma\gamma$ - production: huge background from π^0 - decays,
  need isolated photons: isolation cuts
- γZ or ZZ - production: enough statistics?

Single Quarkonium - production in pp - collisions

[LO: Boer, Pisano, PRD86, 094007; NLO: Ma, Wang, Zhao, PRD88, 014027]

exclusive production of a heavy Quarkonium state (color singlet model):

$$p + p \to (\eta, \chi, ...) + X$$

S-waves: L=0, J=0: $\eta : \; ^1S_0^{(1)}$

P-waves: L=1, J=0,2: $\chi_{0,2} : \; ^3P_{0,2}^{(1)}$

$^{2S+1}L_J$

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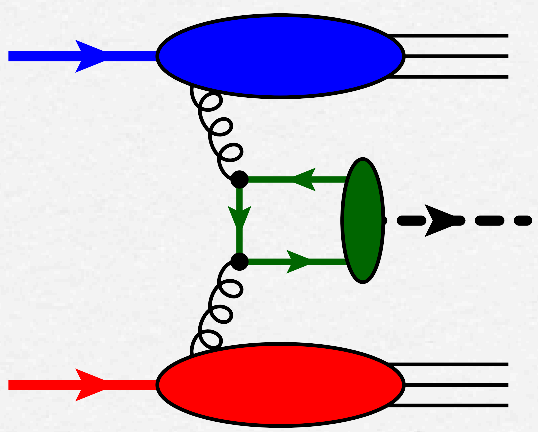

QQ - rest frame: non-relativistic approach

neglect relative quark momenta in hard part

$$\int \frac{d^3\vec{k}}{(2\pi)^3}\, \psi_{00}(\vec{k}) = \frac{1}{\sqrt{4\pi}} R_0(0)$$

$$\int \frac{d^3\vec{k}}{(2\pi)^3}\, k^\alpha \psi_{1L_Z}(\vec{k}) = -i\varepsilon^\alpha_{L_Z}(q)\sqrt{\frac{3}{4\pi}} R_0'(0)$$

no contamination from quark sector (at LO)

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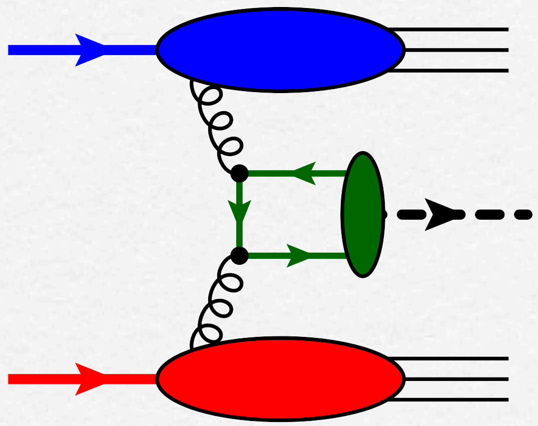

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TMD - formalism ($q_T \sim \Lambda$, $Q = M_Q$):

$$\frac{d\sigma(\eta)}{dyd^2q_T} = C_\eta([f_1^g \otimes f_1^g] - [h_1^g \otimes h_1^g]) \qquad \frac{d\sigma(\chi_0)}{dyd^2q_T} = C_{\chi_0}([f_1^g \otimes f_1^g] + [h_1^g \otimes h_1^g]) \qquad \frac{d\sigma(\chi_2)}{dyd^2q_T} = C_{\chi_2}([f_1^g \otimes f_1^g])$$

- (in principle) possible to extract both TMD - structures!
- Not possible to tune the hard scale, $Q = M_Q$ not that large!
- Transv. Momentum q_T must be very small

$\Upsilon(J/\psi) + \gamma$ - production at the LHC

[den Dunnen, Lansberg, Pisano, M.S., PRL112, 212001 (2014)]

➞ production of back-to-back Quarkonium - Photon pairs ($q_T \ll Q$: TMD factorization)

➞ need colour singlet final state:

Quarkonium (Υ or J/ψ) must be exclusively produced (Color Singlet Model)

Photon needs to be isolated, avoid photon fragmentation

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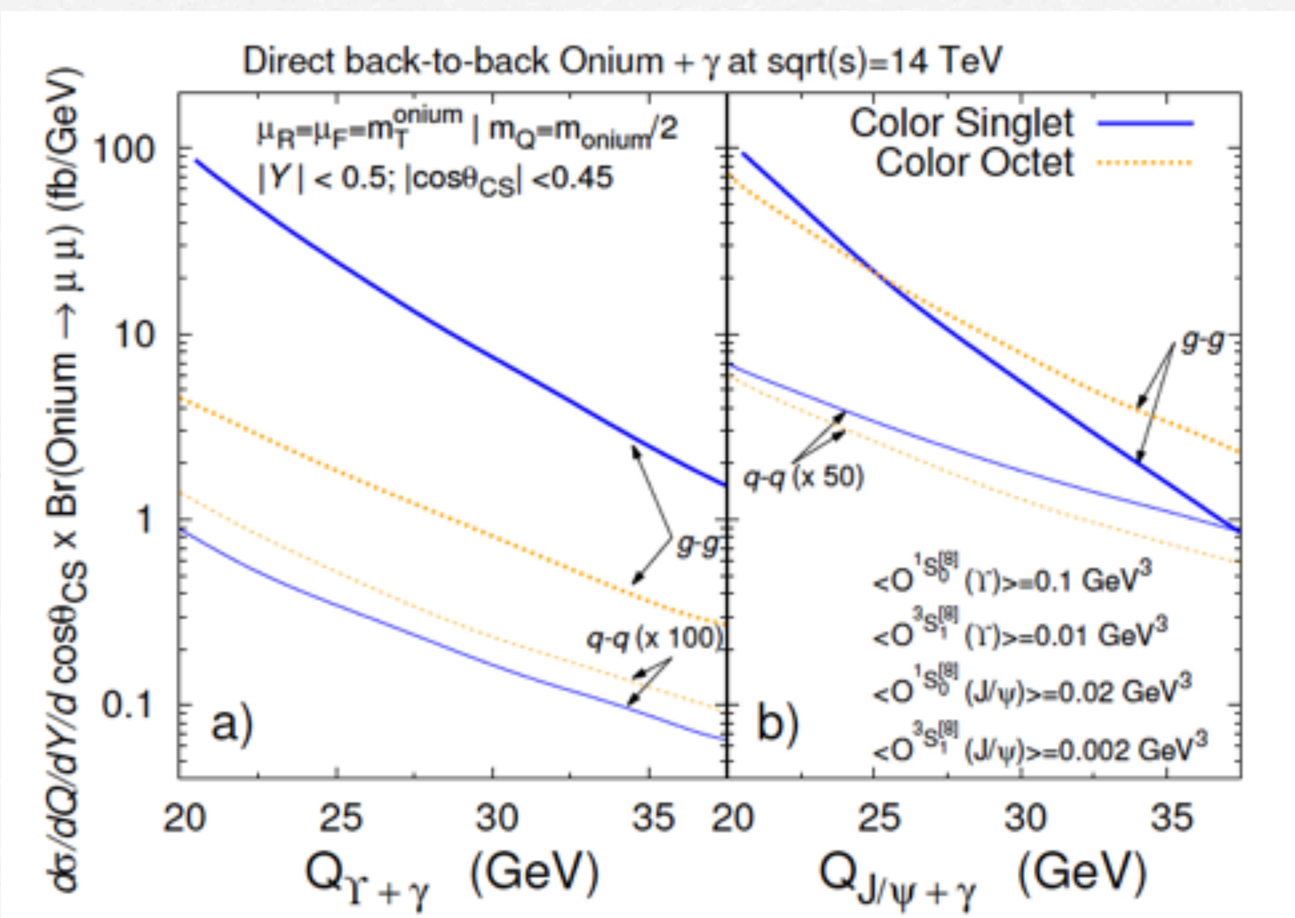
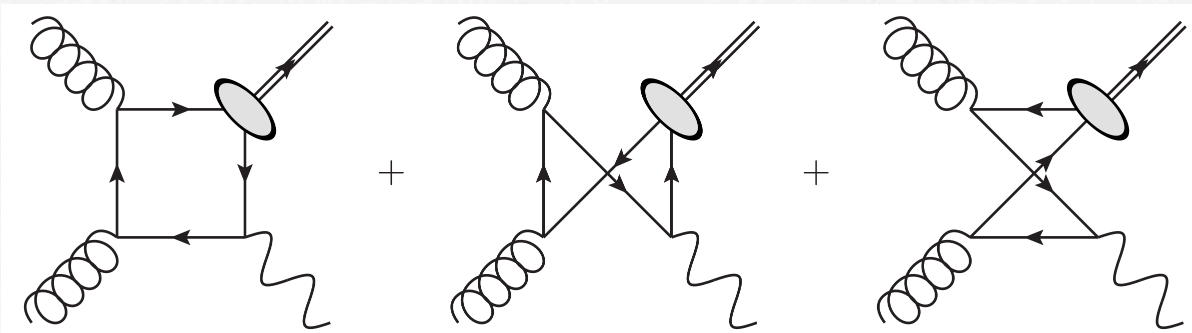
q_T - integrated cross section at the LHC



- main contribution from gluon fusion
- Υ - production:
  Color Octet (Fragm.) ≪ Color Singlet ✔
- J/ψ - production:
  Color Octet ≃ Color Singlet ✗
  isolation of J/ψ?
- At $Q = 20$ GeV, cross section ≃ 100 fb
  large enough for reasonable statistics
  already at 7 TeV (on tape at ATLAS)

TMD result at $q_T \ll Q$

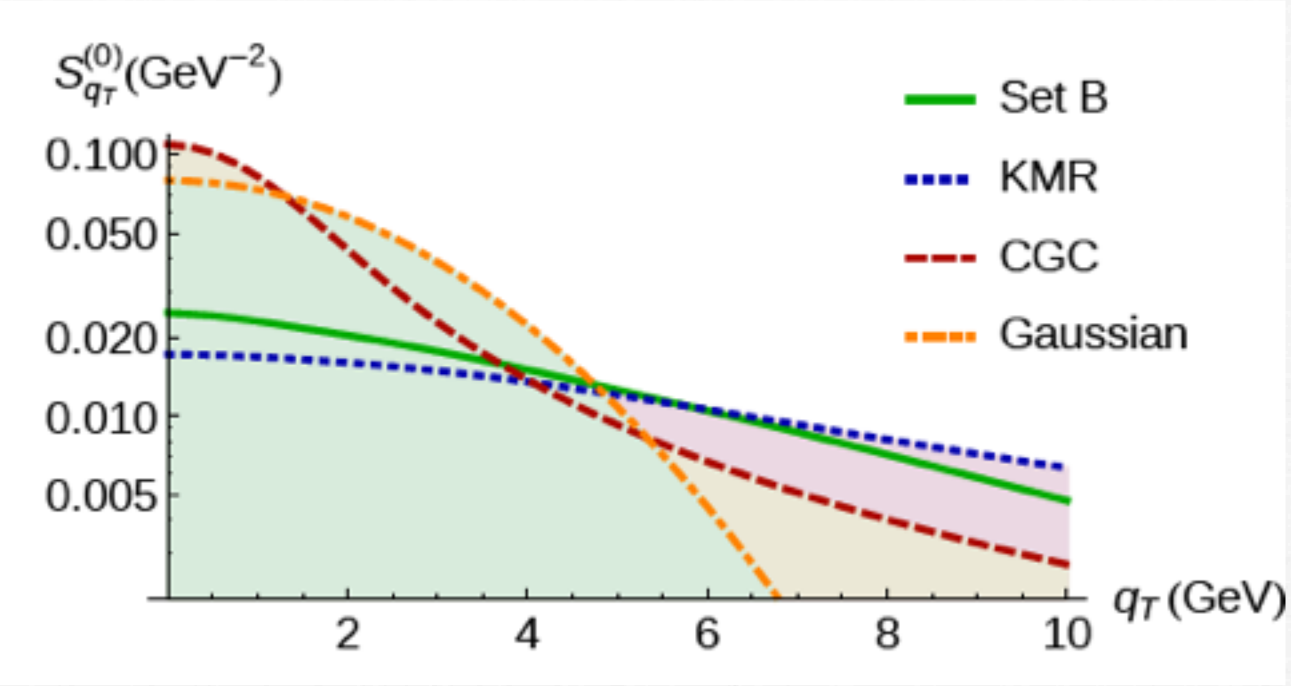


$$q^\mu = P^\mu_\gamma + P^\mu_{J/\psi}$$
$$Q^2 = (P_\gamma + P_{J/\psi})^2$$
$$q_T = P_{\gamma,T} + P_{J/\psi,T}$$

$$\frac{d\sigma}{dY\, dQ\, d^2 q_T\, d\Omega} = C_{J/\psi} \frac{Q^2 - M^2_{J/\psi}}{s Q (Q^2 + q_T^2)} \Big(F_1\big(\tfrac{Q}{M_{J/\psi}}, \cos\theta\big)\, \mathcal{C}[f_1^g\, f_1^g]$$
$$+ F_3\big(\tfrac{Q}{M_{J/\psi}}, \cos\theta\big) \big(\mathcal{C}[w_3\, f_1^g\, h_1^{\perp g}] + \{x_a \leftrightarrow x_b\}\big) \cos(2\phi)$$
$$+ F_4\big(\tfrac{Q}{M_{J/\psi}}, \cos\theta\big)\, \mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}] \cos(4\phi) + \mathcal{Q}(q_T/Q) \Big)$$

- Factors F_1, F_3, F_4 perturbatively at LO → NLO: future work...
- no F_2 - term → pure f_1^g - extraction from q_T - distribution possible
- 2-particle final state: azimuthal $\cos(2\phi)$ and $\cos(4\phi)$ - modulation
- Advantages compared to Single Exclusive η - production pp → ηX:
  - can tune the hard scale Q, probe TMD evolution
  - larger q_T - distributions can be probed

LHC Predictions at central rapidity ($y_\gamma = y_Q = 0$):



$$\frac{1}{\sigma}\frac{d\sigma^n}{dq_T} \equiv 2|\boldsymbol{q}_T| \frac{\int_{-\pi}^{\pi} d\phi \, \cos n\phi \, d\sigma}{\int_0^{q_{T\max}^2} dq_T^2 \int_{-\pi}^{\pi} d\phi \, d\sigma}$$

Set B / KMR:

f_1^g ↔ Parameterizations of the "unintegrated Parton Distribution" based on HERA data

$h_1^{\perp g}$ ↔ Saturation of positivity bound

CGC:

Model calculation of f_1^g and $h_1^{\perp g}$ in the Color Glass Condensate model [Metz, Zhou]

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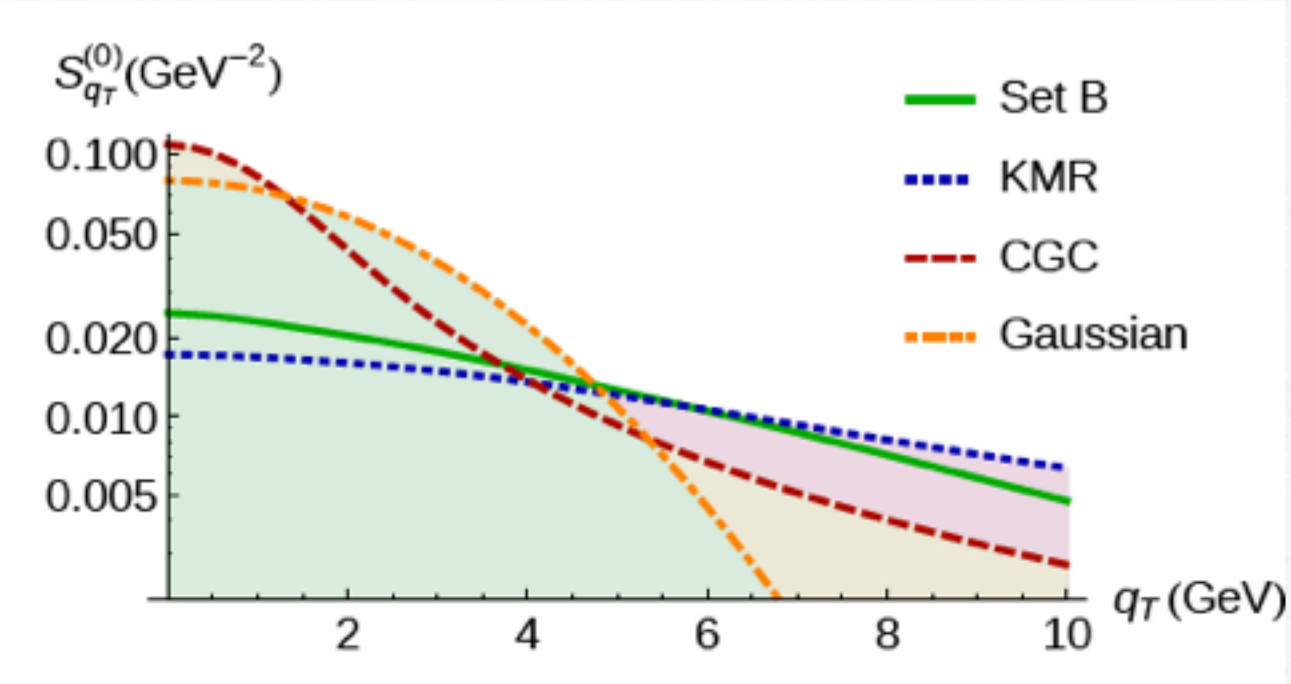

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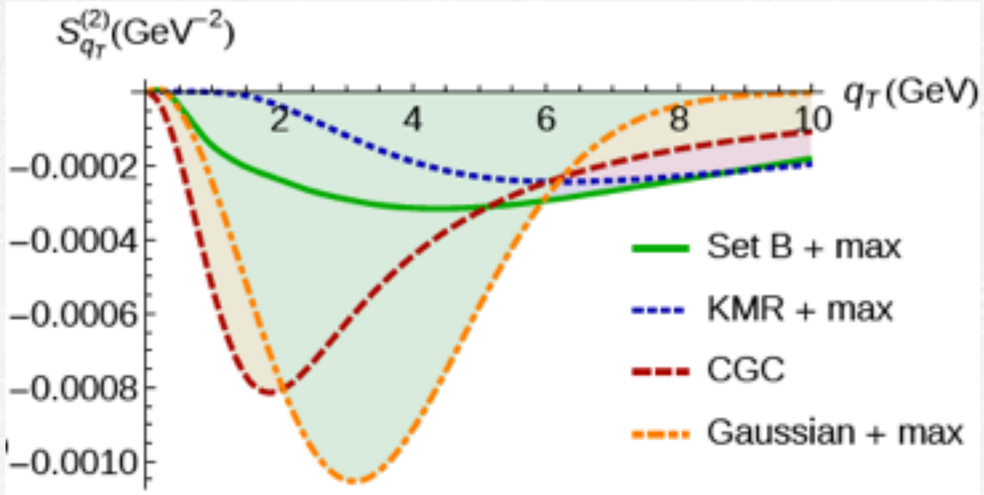
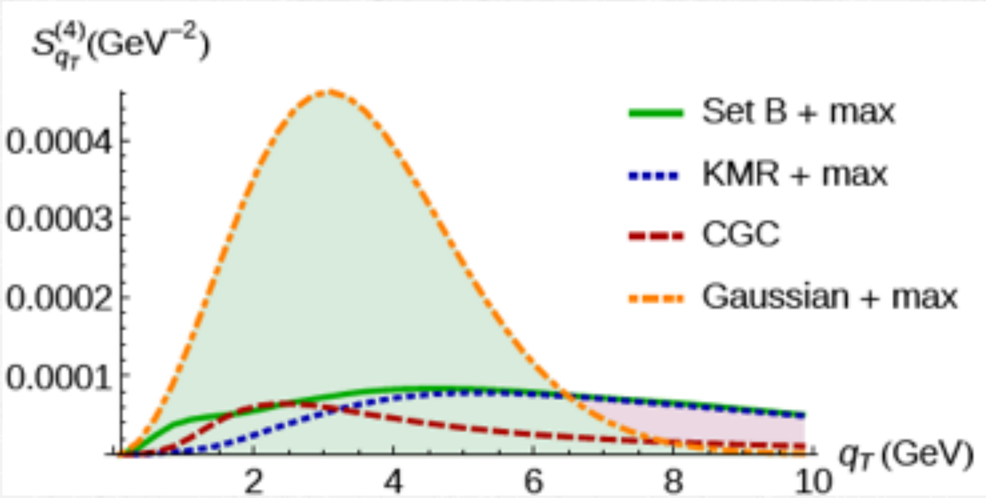
"q_T - integrated" cos(2ϕ) ~ -(2% - 3%)



cos(4ϕ) ~ (0.3% -1%)



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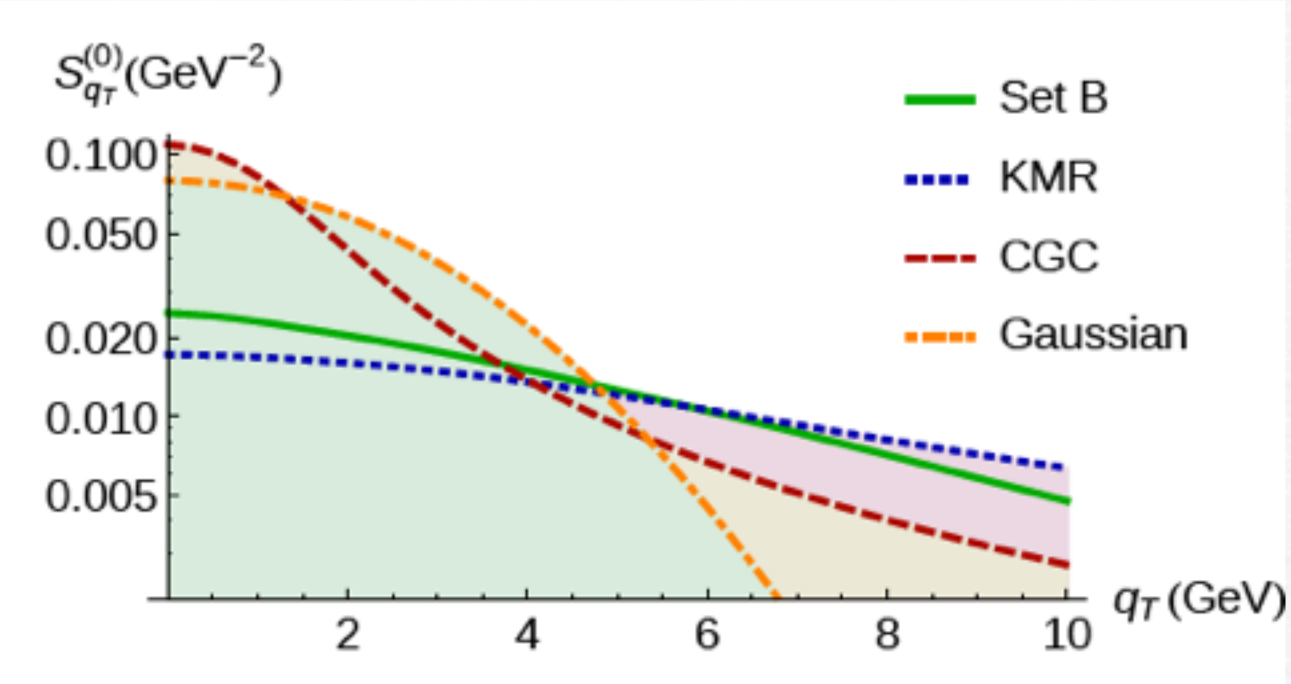

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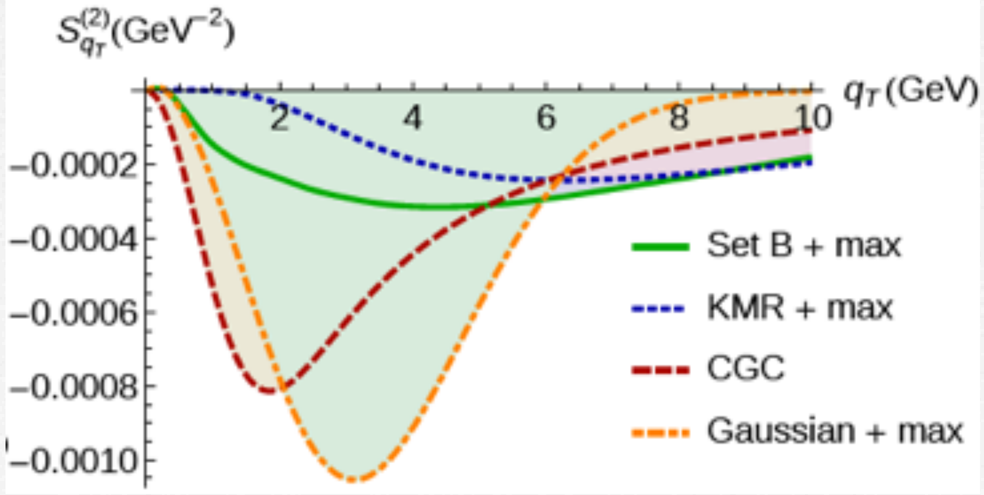

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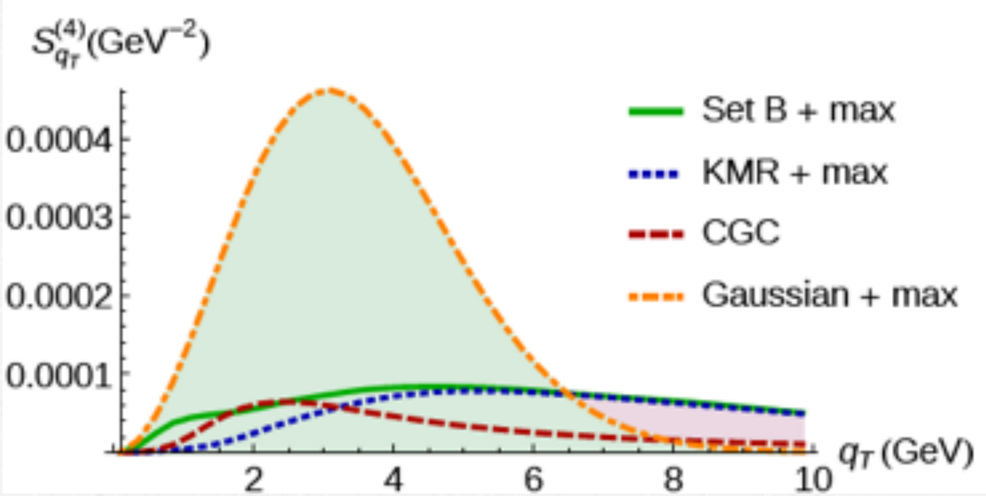

first experimental verification of linearly polarized gluons possible at the LHC!

Summary

- Unpolarized and linearly polarized gluon TMDs are fundamental properties of the nucleon structure!
- Linearly polarized gluons generate azimuthal modulations
  → can be useful tools in particle physics
- Gluon TMDs can be probed in Quarkonium + γ - production with already existing LHC data!