Workshop "Theory LHC France", Nov. 8, 2016, Orsay, France

TMD studies at the LHC

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Institute for Theoretical Physics
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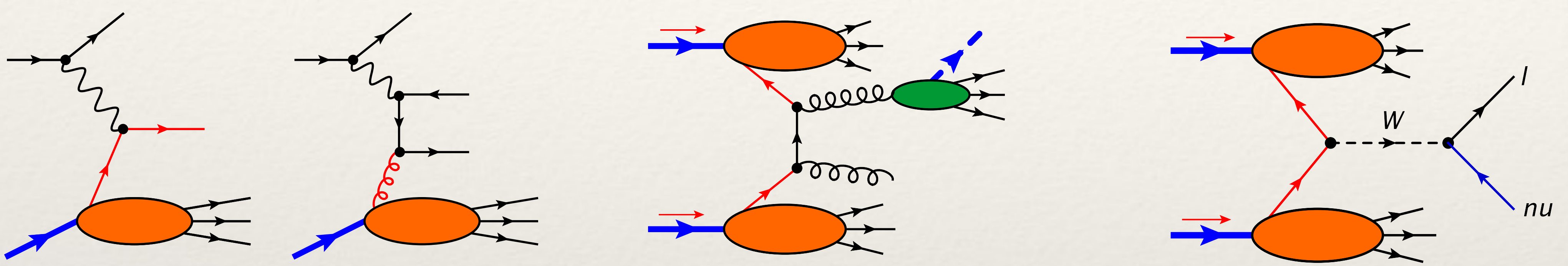
TMD vs. collinear factorization

Collinear factorization in pQCD

- applicable to one-scale processes, e.g. 1-particle inclusive processes



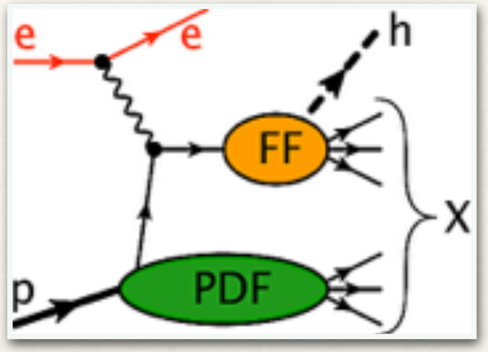
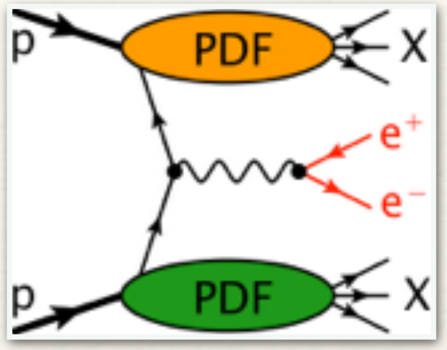
$$\frac{d\sigma}{dx\, dQ^2}$$

- Cross sections at high energies ➙ (hard part) × (soft parts)
- hard part ➙ pQCD (NLO, NNLO,...) ; soft parts ➙ universal, 1-dim

collinear parton distributions

$$q(x,\mu)\,,\ \bar{q}(q,\mu)\,,\ G(x,\mu)$$

- Collinear factorization: 2 (or more...)-particle inclusive processes

SIDIS   Drell-Yan

two scales: hard scale Q + final state transverse momentum q_T

→ integrated observables $\int d^2 q_T \, w(q_T) \, \frac{d\sigma}{dx \, dQ^2 \, dq_T} \equiv \langle w(q_T) \rangle$

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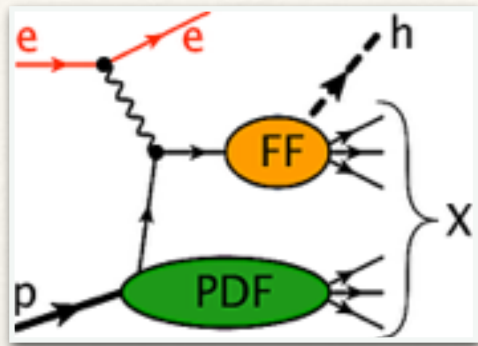

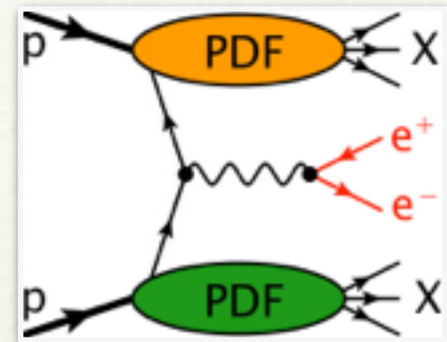

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one scale ➙ collinear factorization ok,
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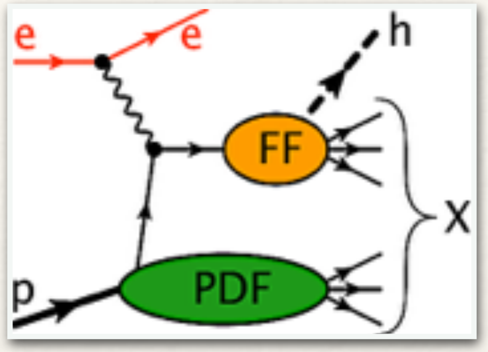
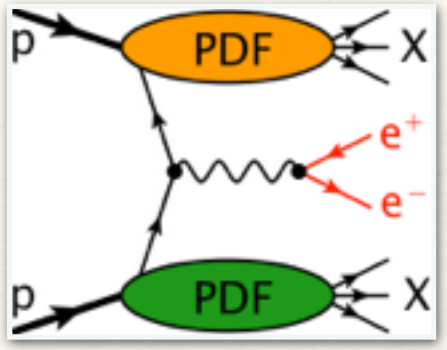
SIDIS 

 Drell-Yan

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$$\frac{d\sigma}{dq_T}(\Lambda_{\rm QCD} \ll q_T \ll Q)$$

large logs in the hard part (gluon radiation) $\log^n(q_T/Q)$
→ CSS-resummation → coll. fact. still applicable

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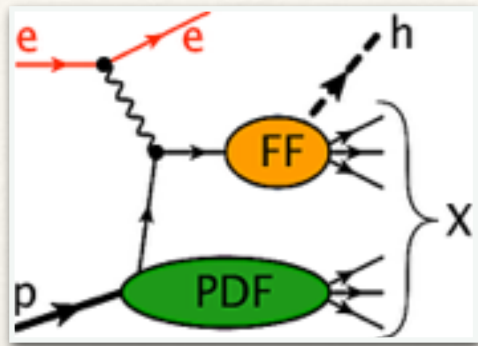

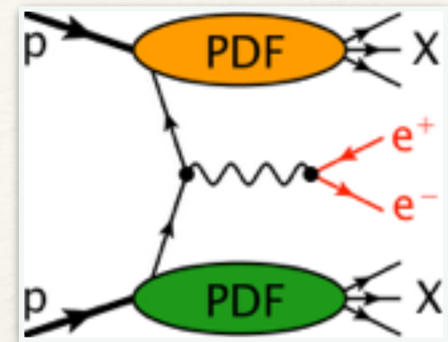

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➙ Transverse momentum dependent (TMD) factorization!

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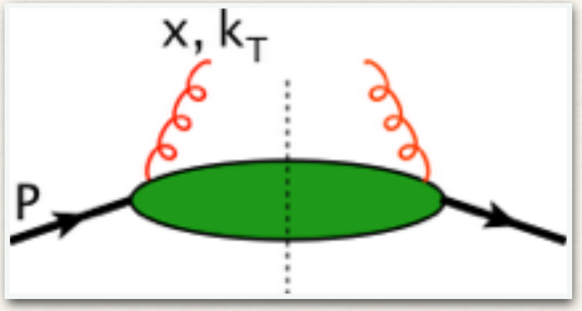

TMD gluonic matrix element

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

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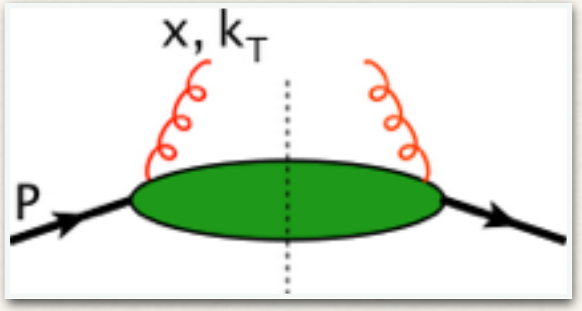

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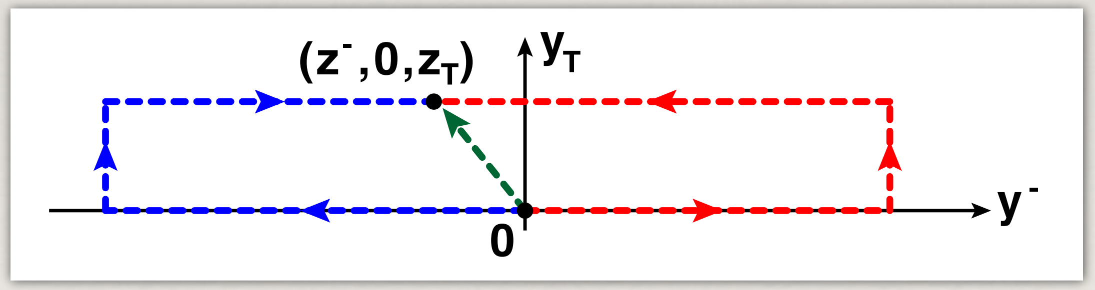
Wilson line in fundamental representation

Color Gauge invariant definition of TMDs ➙ Wilson line

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

➙ Wilson line for TMD:
nontrivial, process dependent:



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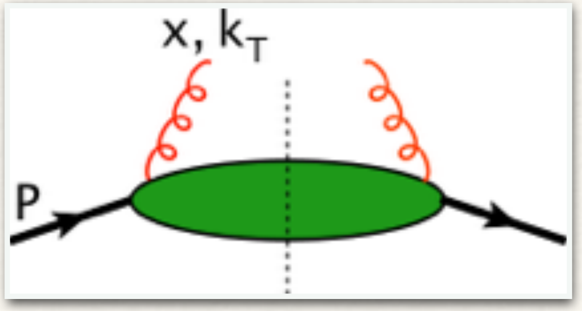

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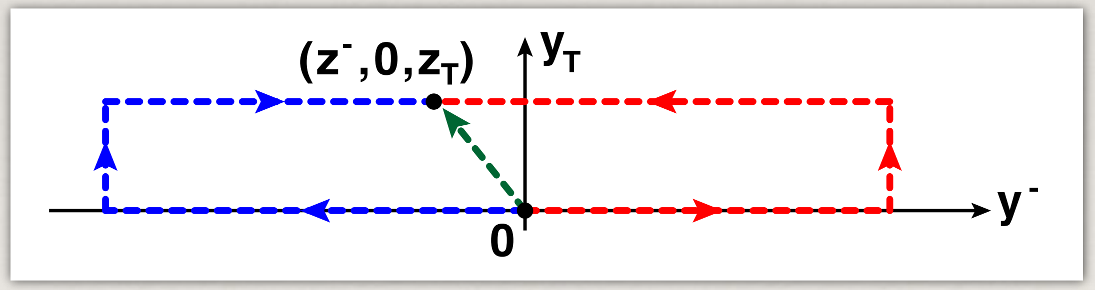

past-pointing WL →
Initial State Interactions:
pp → color singlet + X (DY-type)

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

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

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

Proper Definition & Soft function

[Collins; Sun, Xiao Yuan; Aybat, Rogers; recent work: 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

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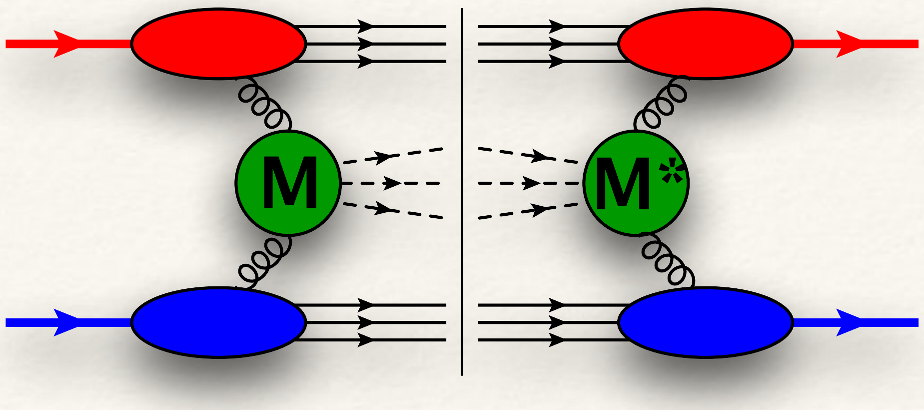
Parameterization

$\Gamma^{[T-even]}(x, \vec{k}_T)$			$\Gamma^{[T-odd]}(x, \vec{k}_T)$	
		flip		**flip**
U	f_1^g	$h_1^{\perp g}$		
L	$g_{1L}^{\perp g}$			$h_{1L}^{\perp g}$
T	$g_{1T}^{\perp g}$		$f_{1T}^{\perp g}$	h_1^g $h_{1T}^{\perp g}$

[Mulders, Rodriues, PRD 63,094021]

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

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



General TMD expression for gluon fusion:

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

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

Calculation of partonic amplitudes
➙ convenient to use gluon polarization vectors
➙ helicity amplitudes

$$\varepsilon^\mu_\lambda(k_a) = (0, 1, i\lambda, 0)/\sqrt{2}$$

$$\delta_T^{\mu\nu} = \sum_\lambda \varepsilon^\mu_\lambda(k_{a/b})(\varepsilon^\nu_\lambda)^*(k_{a/b})$$

Helicity correlator:

$$\Gamma_{\lambda_1\lambda_2}(x, \vec{k}_T) \equiv \Gamma^{ij}(x, \vec{k}_T)\,(\varepsilon^i_{\lambda_1}(k))^*\,(\varepsilon^j_{\lambda_2}(k))^* =$$

$$\frac{1}{2}(\,\delta_{\lambda_1,\lambda_2}\,f_1^g(x, \vec{k}_T^2)\;+\;\delta_{\lambda_1,-\lambda_2}\,\frac{(k_x - i\lambda_1 k_y)^2}{2M^2}\,h_1^{\perp g}(x, \vec{k}_T^2))$$

helicity non-flip

helicity flip

General gluon fusion - structures

General TMD cross section in the helicity formalism

$$\frac{d\sigma}{d^4q...}(q_T \ll Q) \propto \mathcal{C}[\Gamma_{\lambda_a \lambda_{a'}}(x_a, k_{aT})\, \Gamma_{\lambda_b \lambda_{b'}}(x_b, k_{bT})] \left(\mathcal{M}_{\lambda_a \lambda_b} (\mathcal{M}_{\lambda_{a'} \lambda_{b'}})^*\right)$$

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Decomposition into four structures

$\mathcal{C}[f_1^g\, f_1^g]\,\left(\mathcal{M}_{\lambda_a\lambda_b}\,(\mathcal{M}_{\lambda_a\lambda_b})^*\right) \longrightarrow F_1(Q, \Omega, \ldots)$ ➞ helicity non-flip, ϕ - independent, survives q_T-integration

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$\mathcal{C}[w_2\, h_1^{\perp g}\, h_1^{\perp g}]\,\left(\mathcal{M}_{\lambda_a,\lambda_a}\,(\mathcal{M}_{-\lambda_a,-\lambda_a})^*\right)$ → $F_2(Q,\Omega,...)$ ➝ double helicity flip, ϕ - independent

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$$\mathcal{C}[w_{3a}\, h_1^{\perp g}\, f_1^g]\;(\mathcal{M}_{\lambda_a,\lambda_b}\,(\mathcal{M}_{-\lambda_a,\lambda_b})^*) + \{a \leftrightarrow b\} \longrightarrow F_{3,a}(Q, \Omega, ...)$$

→ single helicity flip, cos(2ϕ) / sin(2ϕ) - mode

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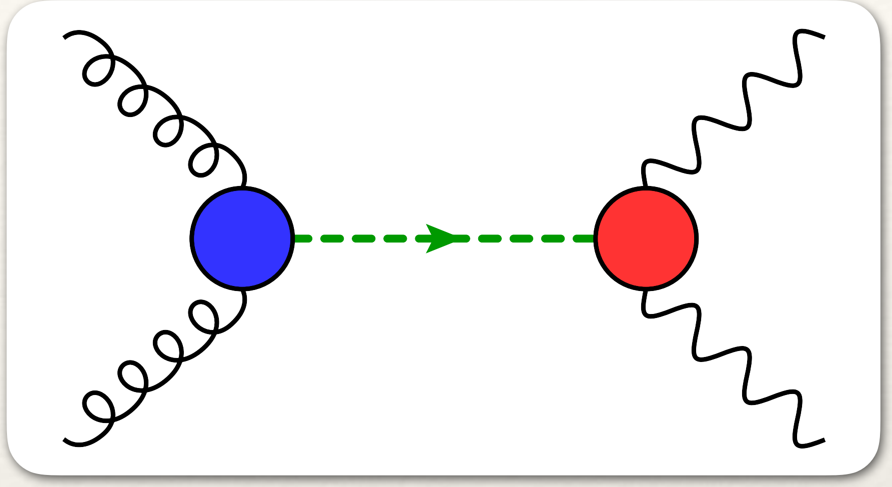
$$\frac{d\sigma^{gg}}{d^4q\; d\Omega}\Big|_{q_T\ll Q} = \hat{F}_1\;[f_1^g \otimes f_1^g] + \hat{F}_2\;[h_1^{\perp g}\otimes h_1^{\perp g}] + \cos(2\phi)\hat{F}_3\;[h_1^{\perp g}\otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi)\hat{F}_4\;[h_1^{\perp g}\otimes h_1^{\perp g}]$$

Linearly polarized gluons as analysis tool

Example: Higgs spin / parity in the $\gamma\gamma$ - decay channel

[Boer, den Dunnen, Pisano, M.S., Vogelsang; PRL 2012, 2013]



most general parameterization of the
$gg \to X_{0/2}$, $X_{0/2} \to \gamma\gamma$ vertices
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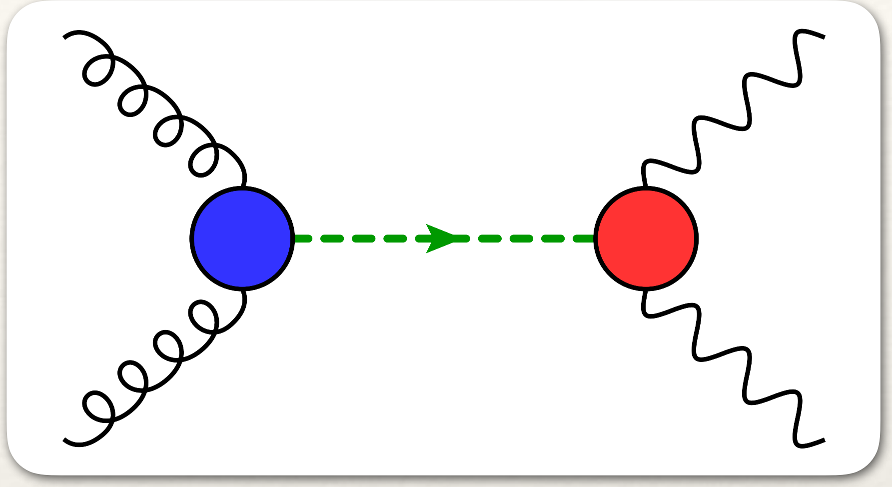

Spin 0:

$$V_{X_0 \to V^\mu(q_1) V^\nu(q_2)} = a_1 q^2 g^{\mu\nu} + a_3 \epsilon^{q_1 q_2 \mu\nu}$$

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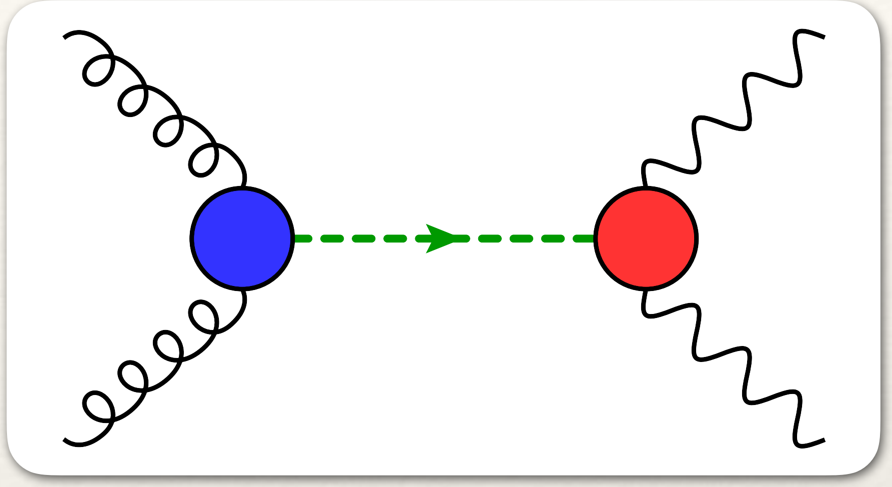

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Spin 2:

$$V_{X_2^{\alpha\beta} \to V^\mu(q_1) V^\nu(q_2)} = c_1 q^2 g^{\mu\alpha} g^{\mu\beta} + c_2 g^{\mu\nu} (q_1 - q_2)^\alpha (q_1 - q_2)^\beta + c_5 \epsilon^{q_1 q_2 \mu\nu} \frac{1}{Q^2} (q_1 - q_2)^\alpha (q_1 - q_2)^\beta$$

$$\frac{d\sigma_2}{d\Omega} = \mathcal{F}_1(c_i,\theta)\ [f_1^g \otimes f_1^g] + \mathcal{F}_2(c_i,\theta)\ [h_1^g \otimes h_1^g] + \mathcal{F}_3(c_i,\theta)\ [h_1^g \otimes f_1^g] \cos(2\phi) + \mathcal{F}_3'(c_i,\theta)\ [h_1^g \otimes f_1^g] \sin(2\phi) + \mathcal{F}_4(c_i,\theta)\ [h_1^g \otimes h_1^g] \cos(4\phi)$$

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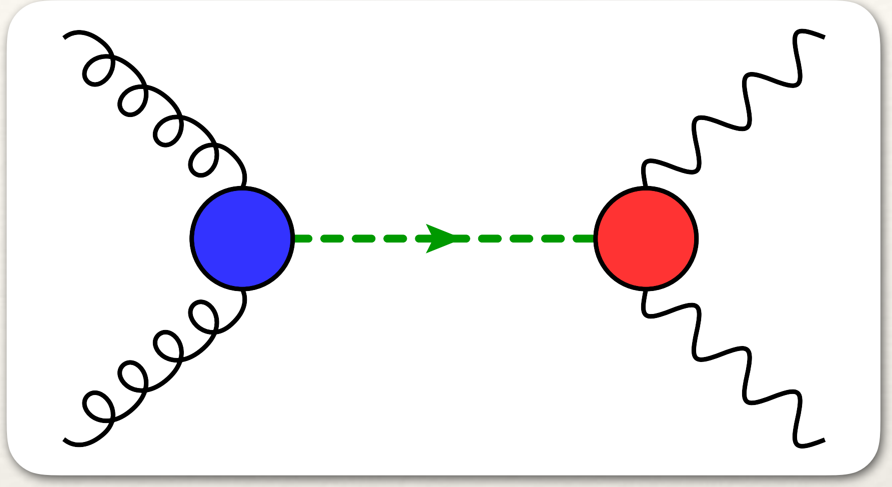

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Spin 2:

$$V_{X_2^{\alpha\beta} \to V^\mu(q_1) V^\nu(q_2)} = c_1 q^2 g^{\mu\alpha} g^{\mu\beta} + c_2 g^{\mu\nu} (q_1 - q_2)^\alpha (q_1 - q_2)^\beta + c_5 \epsilon^{q_1 q_2 \mu\nu} \frac{1}{Q^2} (q_1 - q_2)^\alpha (q_1 - q_2)^\beta$$

$$\frac{d\sigma_2}{d\Omega} = \mathcal{F}_1(c_i,\theta)\ [f_1^g \otimes f_1^g] + \mathcal{F}_2(c_i,\theta)\ [h_1^g \otimes h_1^g] + \mathcal{F}_3(c_i,\theta)\ [h_1^g \otimes f_1^g] \cos(2\phi) + \mathcal{F}_3'(c_i,\theta)\ [h_1^g \otimes f_1^g] \sin(2\phi) + \mathcal{F}_4(c_i,\theta)\ [h_1^g \otimes h_1^g] \cos(4\phi)$$

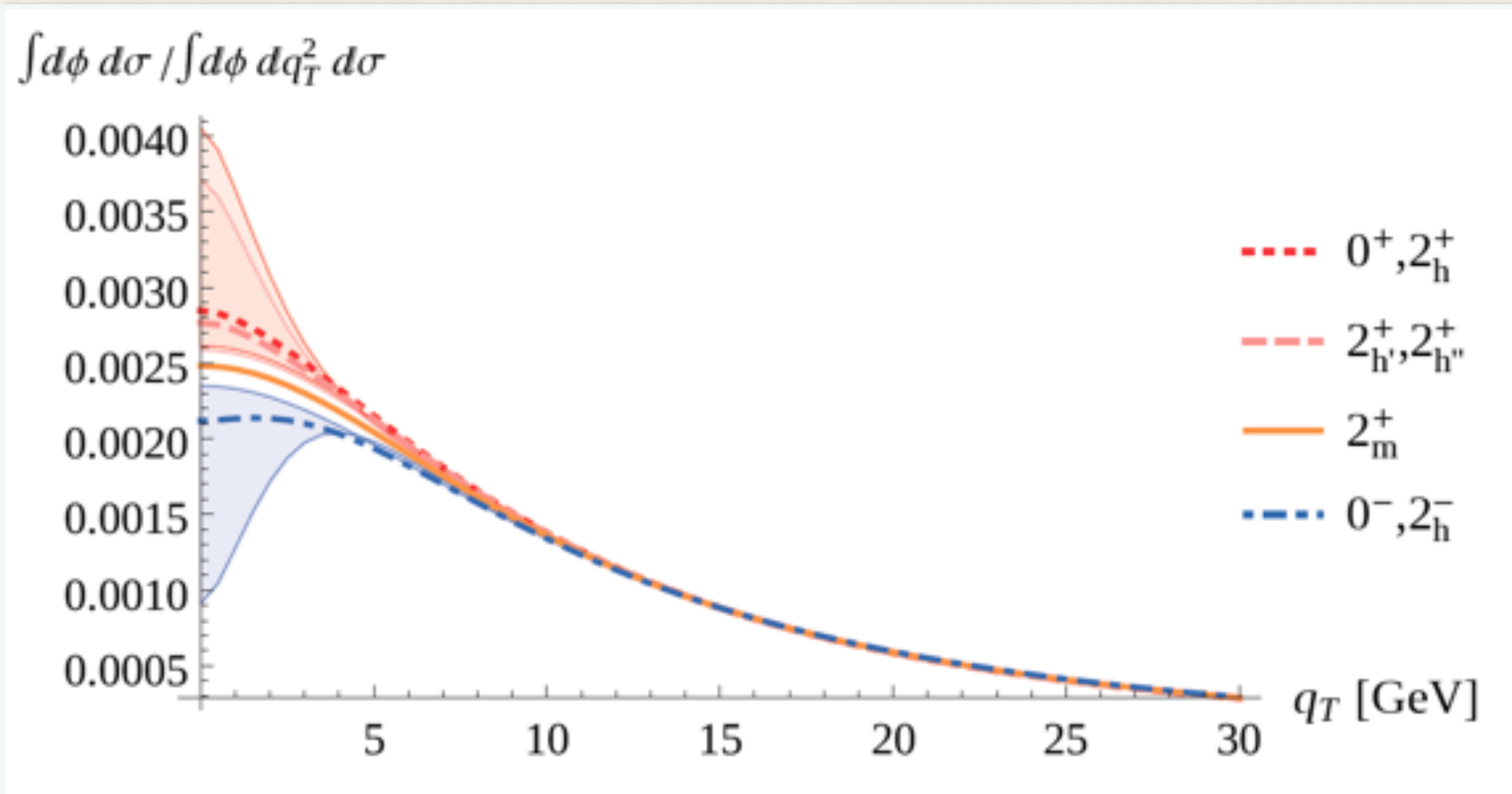
benchmark scenarios

scenario	0^+	0^-	2^+_m	2^+_h	$2^+_{h'}$	$2^+_{h''}$	2^-_h
a_1	1	0	-	-	-	-	-
a_3	0	1	-	-	-	-	-
c_1	-	-	1	0	1	1	0
c_2	-	-	$-\frac{1}{4}$	1	1	$-\frac{3}{2}$	0
c_5	-	-	0	0	0	0	1

azimuthal modulations due to linear polarized gluons!

$\sin(2\phi) \to$ signal for CP-violation

Parity from q_T-dependence



$$\frac{d\sigma}{d^2 q_T} \propto F_1 \; C[f_1^g \; f_1^g] \pm F_2 \; C[w_2 \; h_1^{\perp g} \; h_1^{\perp g}]$$

P-even: increase of at low q_T,
P-odd: decrease (also for Spin-2)

Evolution:
effect only ~ 1% at Q = m_H
[Boer, den Dunnen, NPB 2014]

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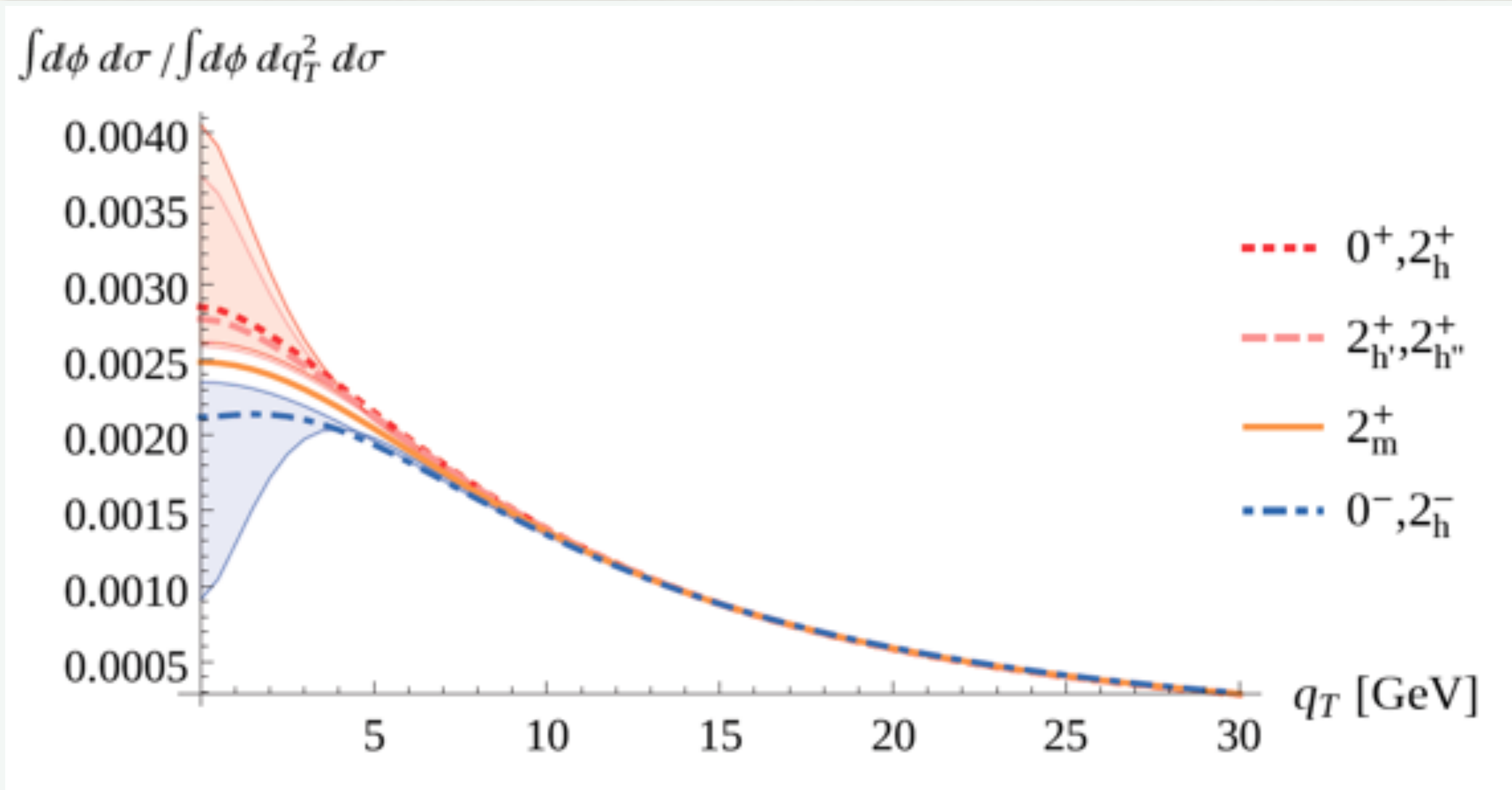

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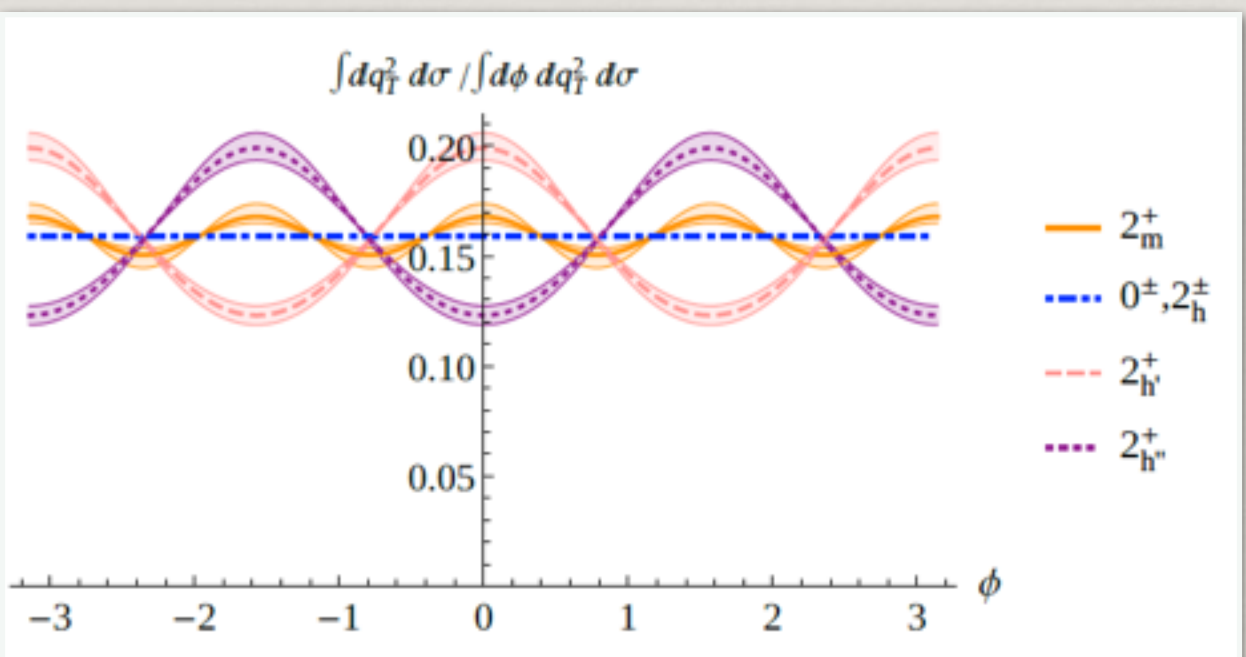
Spin from ϕ-dependence



(pseudo-)scalar, 2_h isotropic

2_m - hyp. → cos(4ϕ)-modulation: ~5% ,

$2_{h',h''}$ - hyp. → cos(2ϕ)-modulation: ~20%

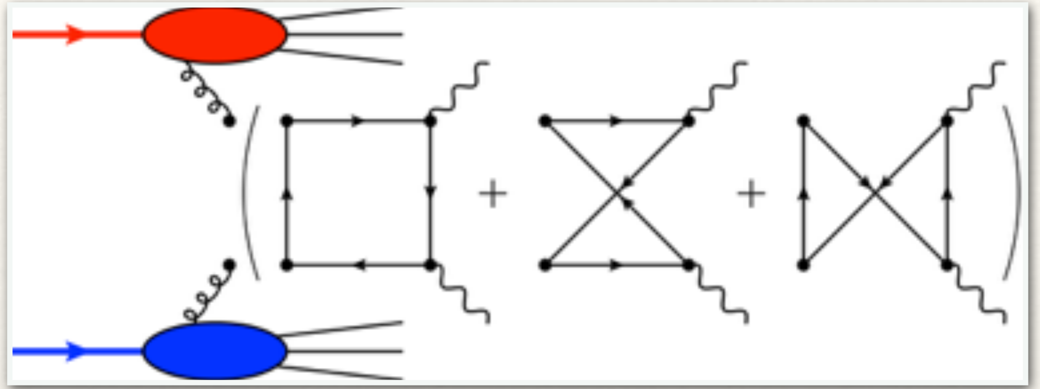
h' and h'' distinguishable!

(unlike in collinear factorization)

Other final states in pp - collisions

$gg \to \gamma\gamma$ at $Q \neq m_H$: QCD background process

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



- contaminations from quark contributions: only $\cos(4\phi)$-modulation purely gluonic
- $\gamma\gamma$ - production: background from π^0 - decays

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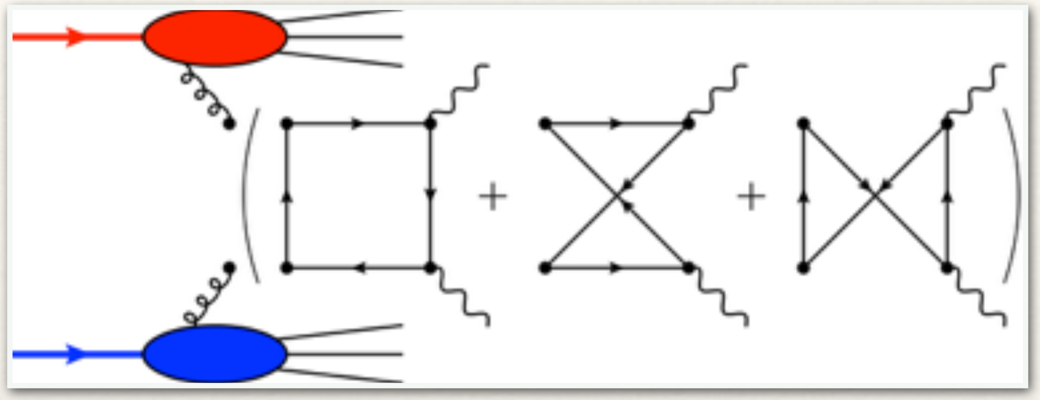

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Single Quarkonium production

[LO: Boer, Pisano, PRD 2012; NLO: Ma, Wang, Zhao, PRD 2012]

(Exclusive) production of a heavy Quarkonium state (color singlet mode):

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

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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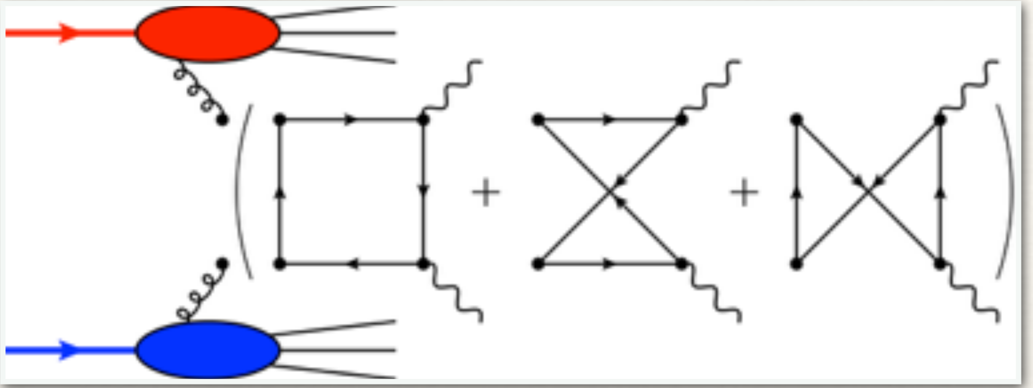

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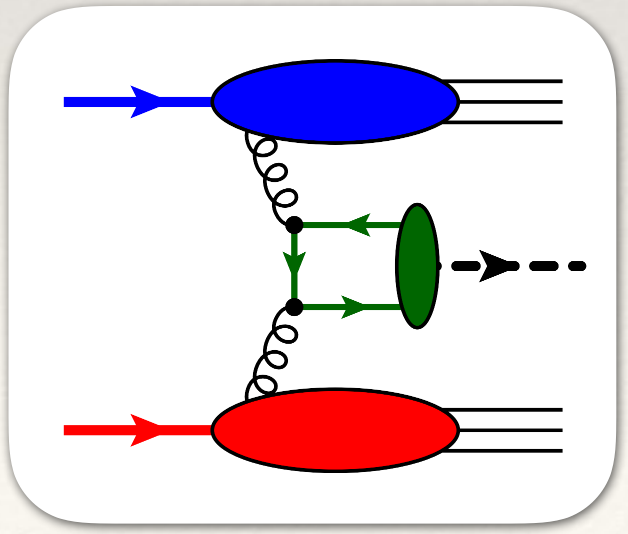


TMD - formalism ($Q = M_Q \gg q_T$):

$$\frac{d\sigma(\eta)}{dy d^2 q_T} = C_\eta([f_1^g \otimes f_1^g] - [h_1^g \otimes h_1^g])$$

$$\frac{d\sigma(\chi_0)}{dy d^2 q_T} = C_{\chi_0}([f_1^g \otimes f_1^g] + [h_1^g \otimes h_1^g])$$

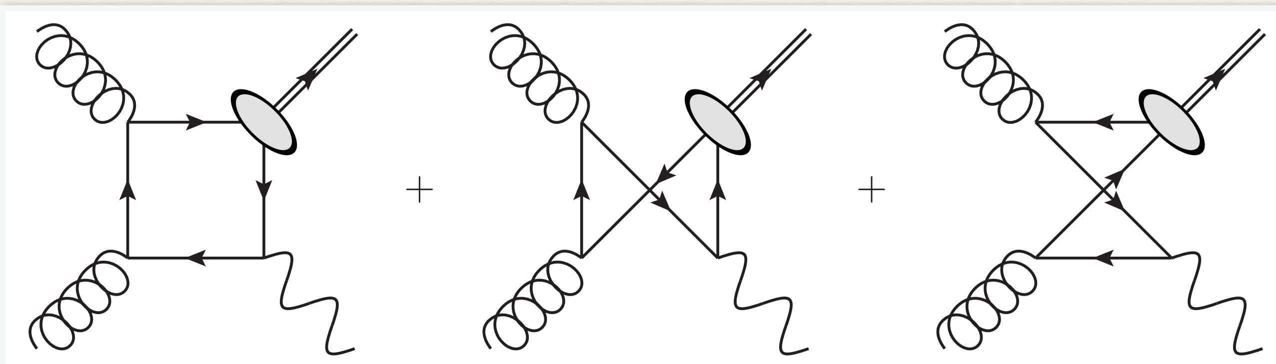
$$\frac{d\sigma(\chi_2)}{dy d^2 q_T} = C_{\chi_2}([f_1^g \otimes f_1^g])$$

- no contamination from quark channel (at LO)
- q_T very small, difficult to measure

Υ(J/ψ)+ γ - production at the LHC

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

$$\left.\frac{d\sigma}{d^4q\,d\Omega}\right|_{q_T \ll Q} = \hat{F}_1\,\mathcal{C}[f_1^g\,f_1^g] + \cos(2\phi)\,\hat{F}_3\left(\mathcal{C}[w_{3a}\,h_1^{\perp g}\,f_1^g] + \{x_a \leftrightarrow x_b\}\right) + \cos(4\phi)\,\hat{F}_4\,\mathcal{C}[w_4\,h_1^{\perp g}\,h_1^{\perp g}]$$



- Hard scale Q adjustable (back-to-back pair)
- main contribution from gluon fusion
- Υ - production:
  Color Octet (Fragm.)« Color Singlet ✔
- F_2 = 0, cos(2ϕ) ~ 3%, cos(4ϕ) ~ 1%!
- Cross section large enough at the LHC

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

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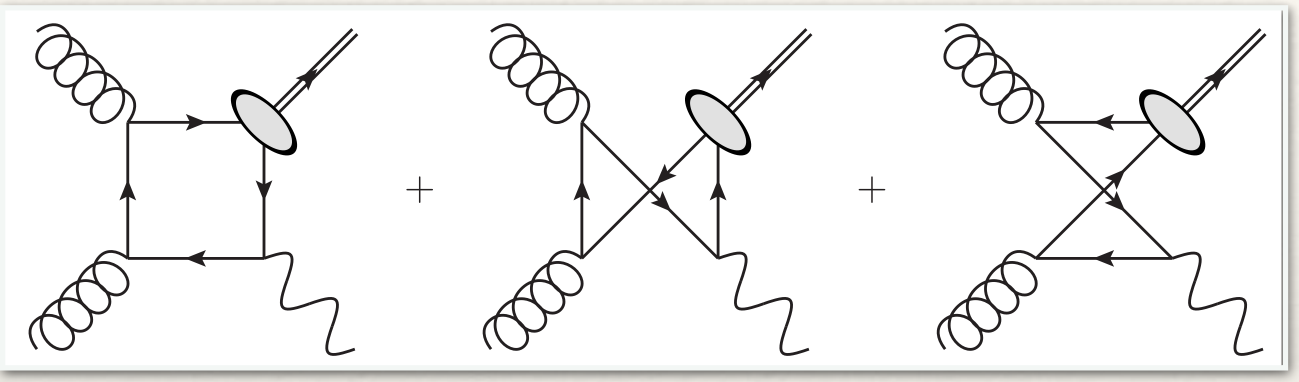

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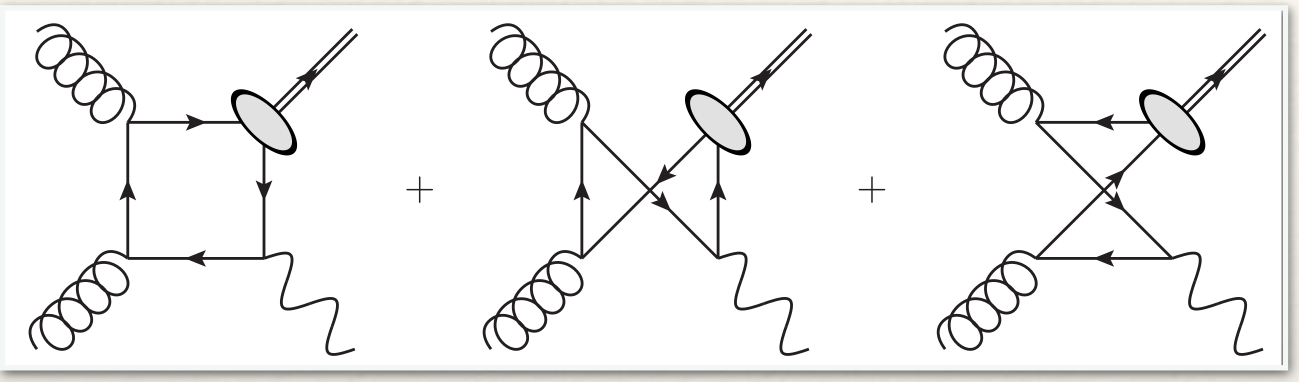

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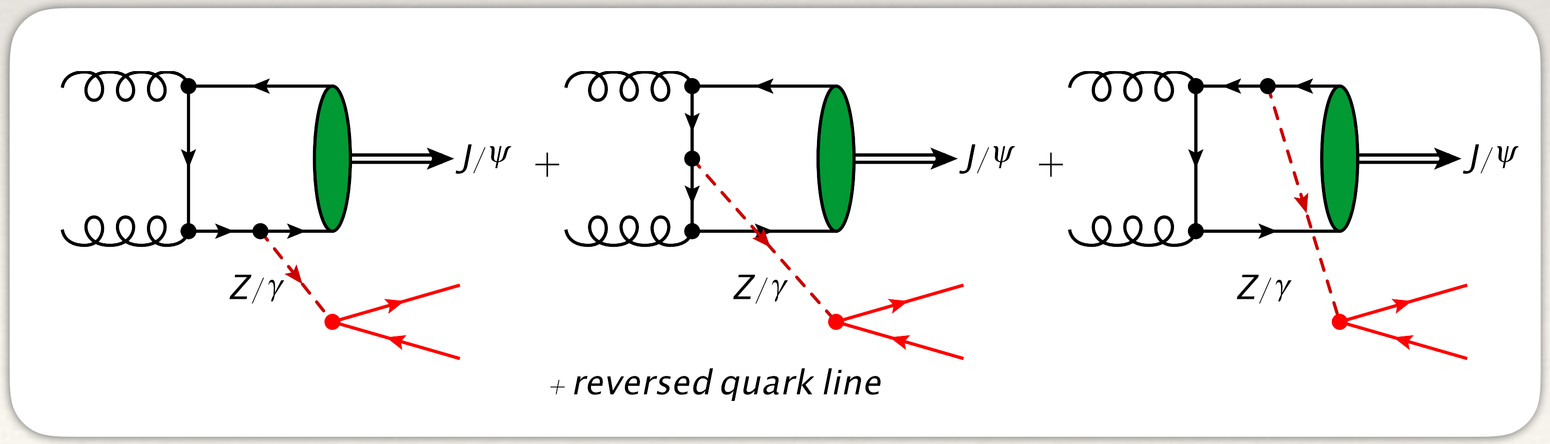
Υ + Z - production at the LHC

[Lansberg, Pisano, M.S., in preparation]



$F_1 \gg F_2, F_3, F_4$

$$\left.\frac{d\sigma}{d^4q}\right|_{q_T\ll Q} = \hat{F}_1\,\mathcal{C}[f_1^g\,f_1^g]$$

ATLAS data exists for q_T - integrated cross section

Summary

- 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
- "Golden" Experiment: Lepton - Nucleon collisions at EIC
- Theory: Evolution of gluon TMDs and higher order calculations become available, need for data fits
- Relations to small-x physics, SCET, …

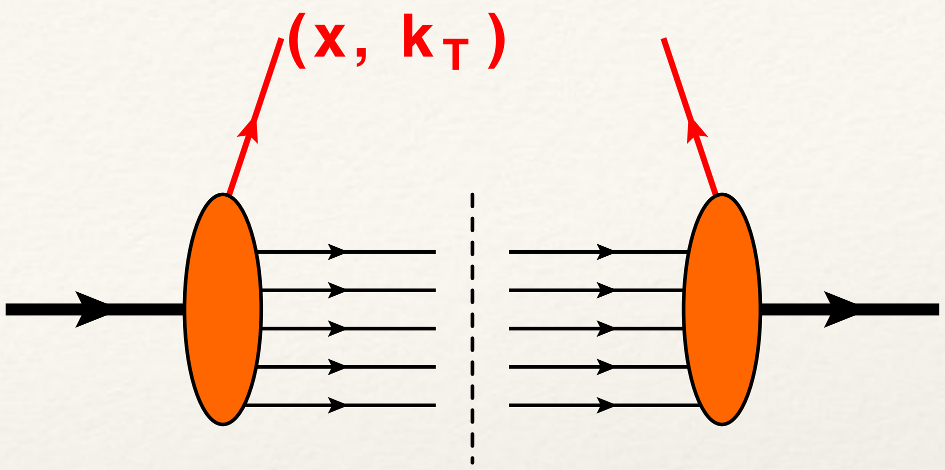
Idea of TMDs:

transverse momentum q_T from "intrinsic" transverse parton momentum k_T

→ different kind of factorization

→ additional degree of freedom of partonic motion

→ study different aspects of hadron spin structure (e.g. 3-d momentum structure, spin-orbit correlations, etc.)



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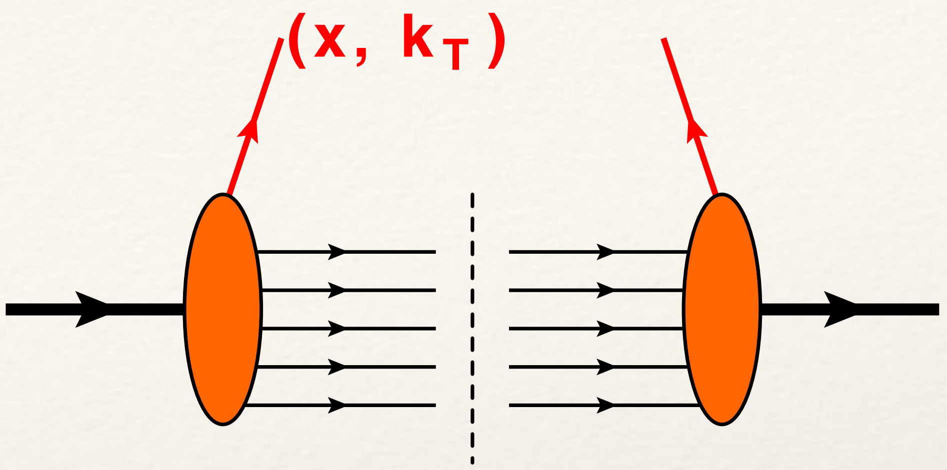
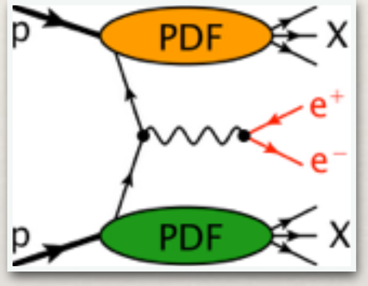


- All-order factorization theorem for, e.g., Drell-Yan



$$W^{\mu\nu} \sim \int d^2k_{aT} d^2k_{bT}\, \delta^{(2)}(\vec{k}_{aT} + \vec{k}_{bT} - \vec{q}_T)\, \mathrm{Tr}[\hat{M}^{\mu} \Phi(x_a, \vec{k}_{aT}) (\hat{M}^{\nu})^{\dagger} \bar{\Phi}(x_b, \vec{k}_{bT})] + Y^{\mu\nu}$$

$q_T \ll Q$ $\qquad$ $q_T \simeq Q$

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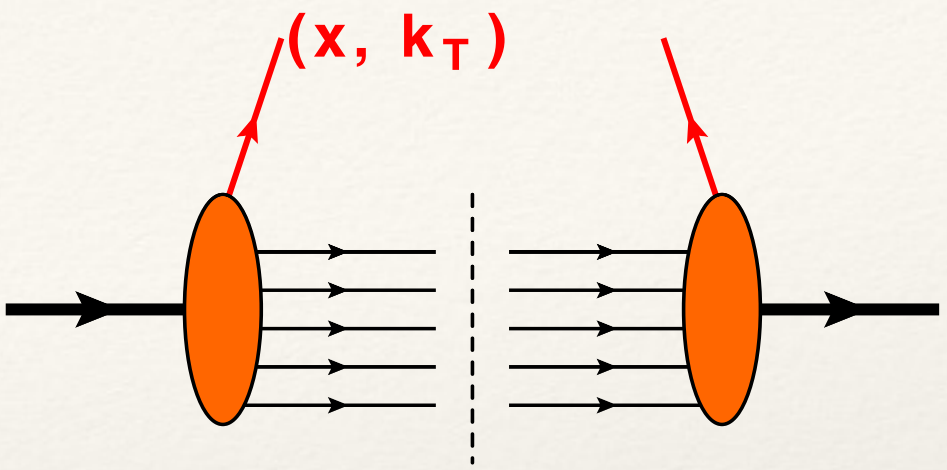

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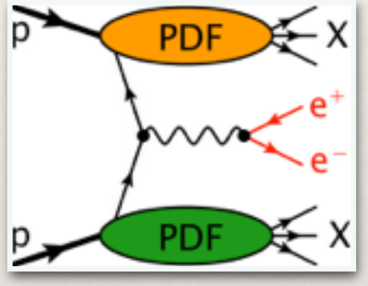

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$q_T \ll Q$ → $q_T \simeq Q$ →

- proven for SIDIS + pp - collisions with color singlet final states

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

“Color Entanglement”

TMD factorization problematic in pp - collisions with a colored final state!

[Collins, Qiu; Rogers, Mulders]

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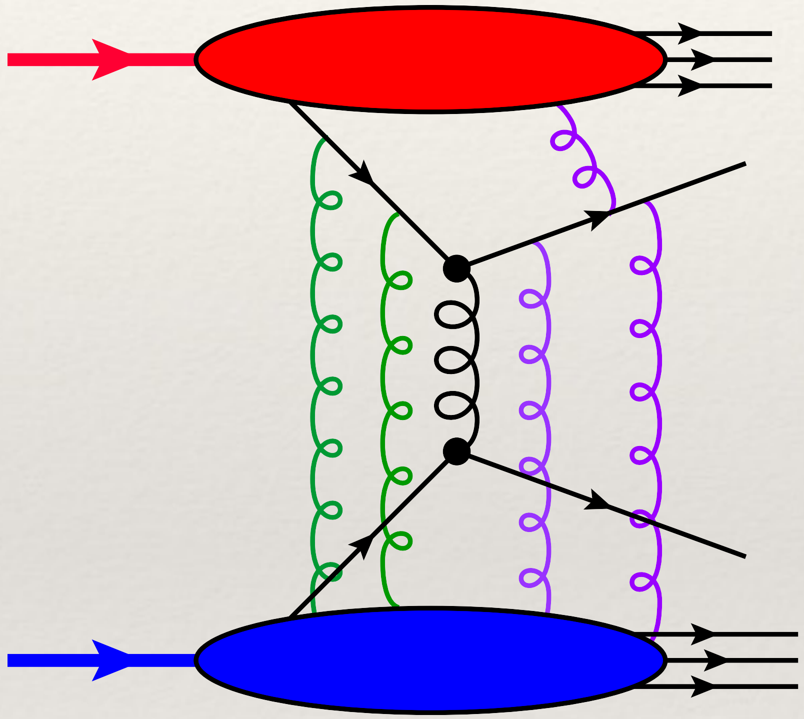
Example: dijet production pp → jet + jet + X



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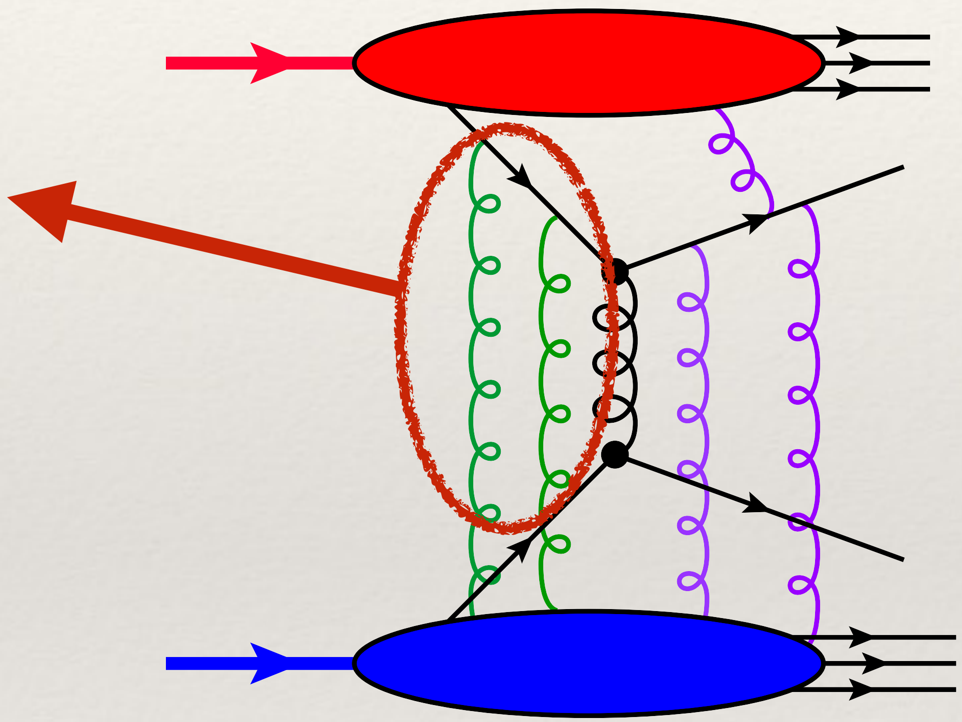

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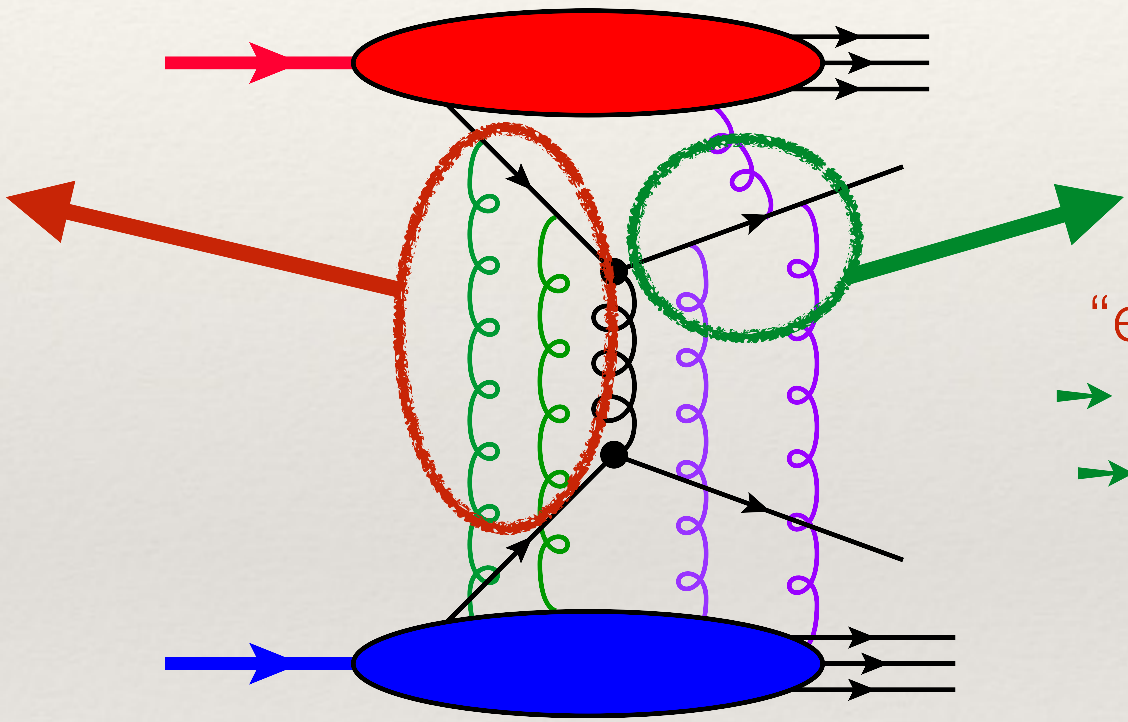

Final State Interactions from both nucleons are “entangled” in color space

→ cannot define Wilson lines

→ TMD factorization invalid

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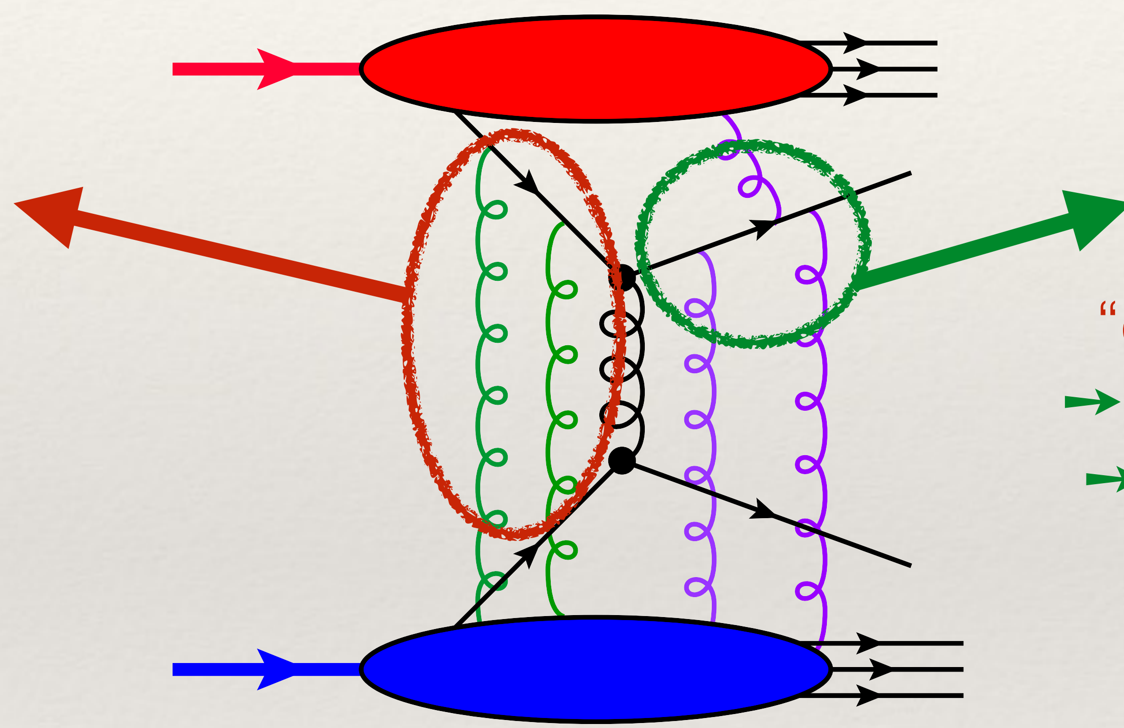

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TMD factorization in pp - collisions only for color singlet final states:

p + p ⟶ leptons, isolated photons, isolated Quarkonia in a color singlet state

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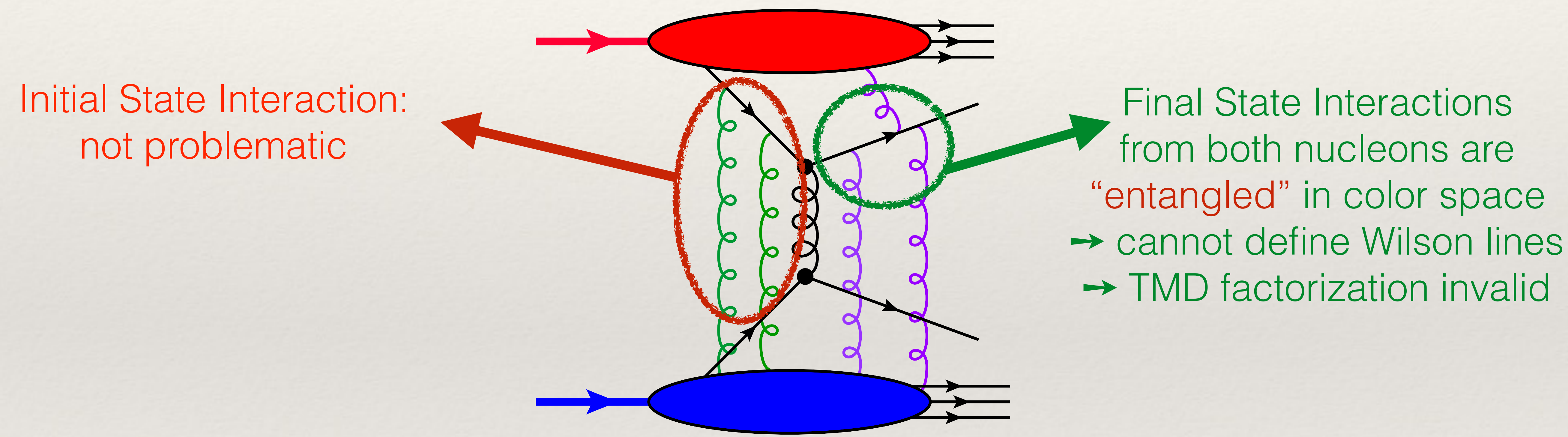

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TMD factorization breaking effects large? small? and why…?

Processes sensitive to gluon TMDs

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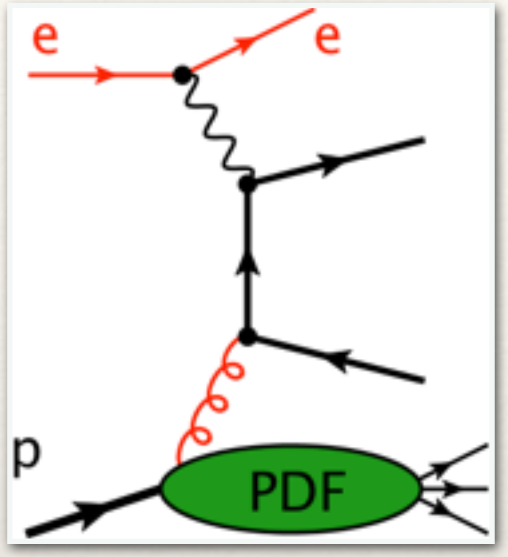


Heavy Quark production in e + p - collisions

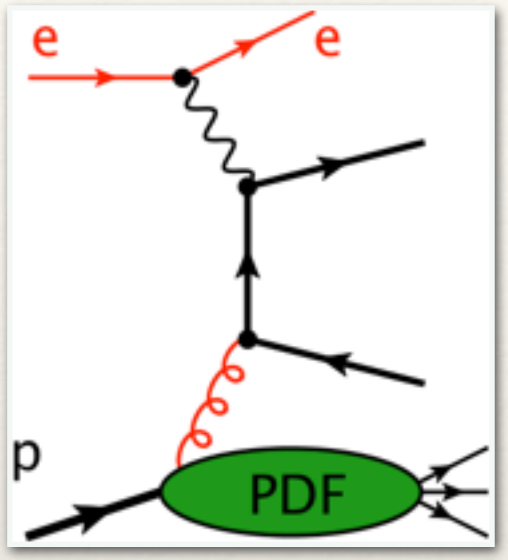
[Boer, Brodsky, Mulders, Pisano, PRL 2011]

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

TMD factorization ok!

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

Processes sensitive to gluon TMDs



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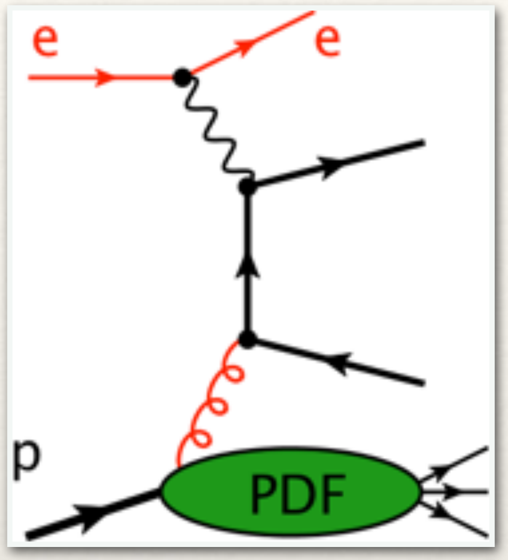
unpolarized cross section:

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

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

Processes sensitive to gluon TMDs



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

gluon TMDs from (pol.) e + p ➝ more talks by van Daal, Silva, Sangem, …