Accessing the gluon TMDs with $J/\psi + \gamma$ SSA at AFTER

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University of Tübingen

in collaboration with W. den Dunnen, J.-P. Lansberg, C. Pisano

Probing the Strong Interactions at AFTER using the LHC beams,
Ecole de Physique des Houches, Jan.13, 2014

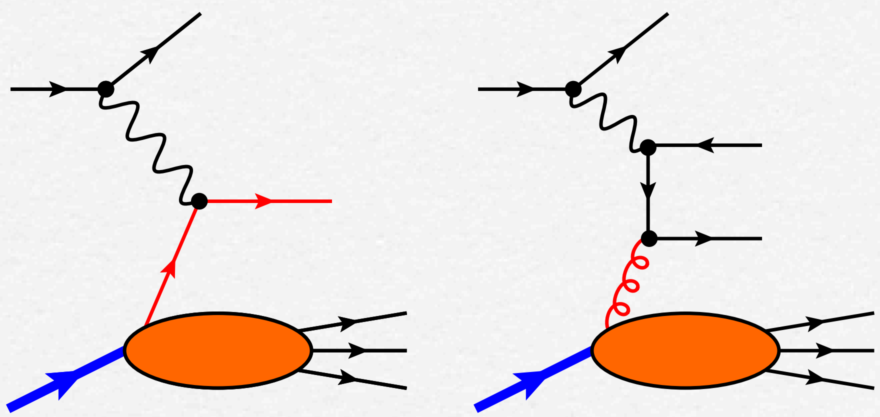
Collinear Factorization

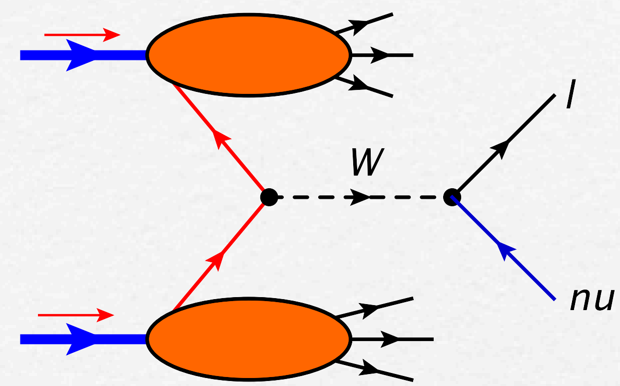
vs.

TMD Factorization

Collinear factorization in pQCD

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





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

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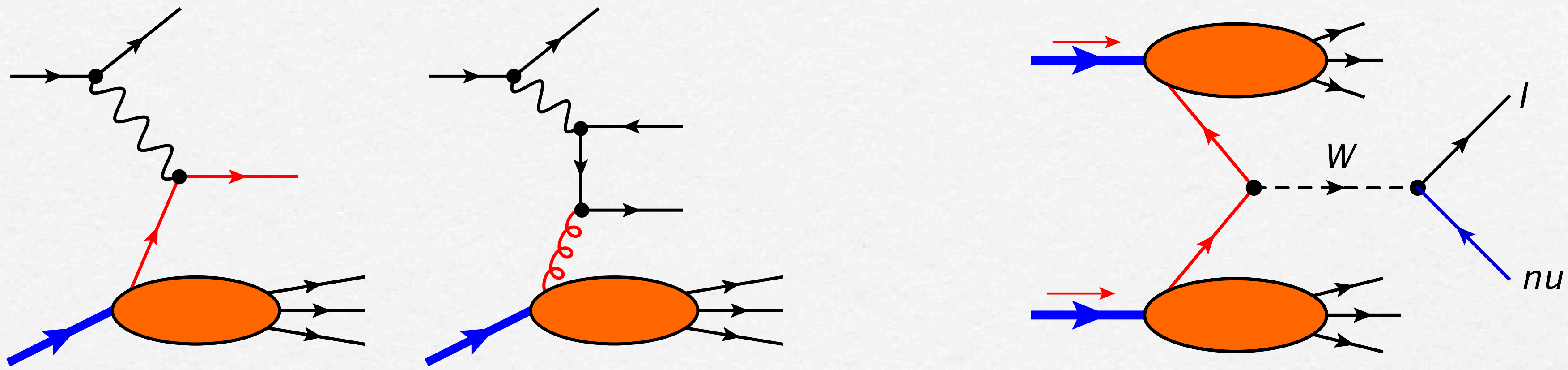

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- Cross sections at high energies ➙ (hard part) × (soft parts)
- hard part ➙ pQCD (NLO, NNLO,...) ; soft parts ➙ universal, 1-dim

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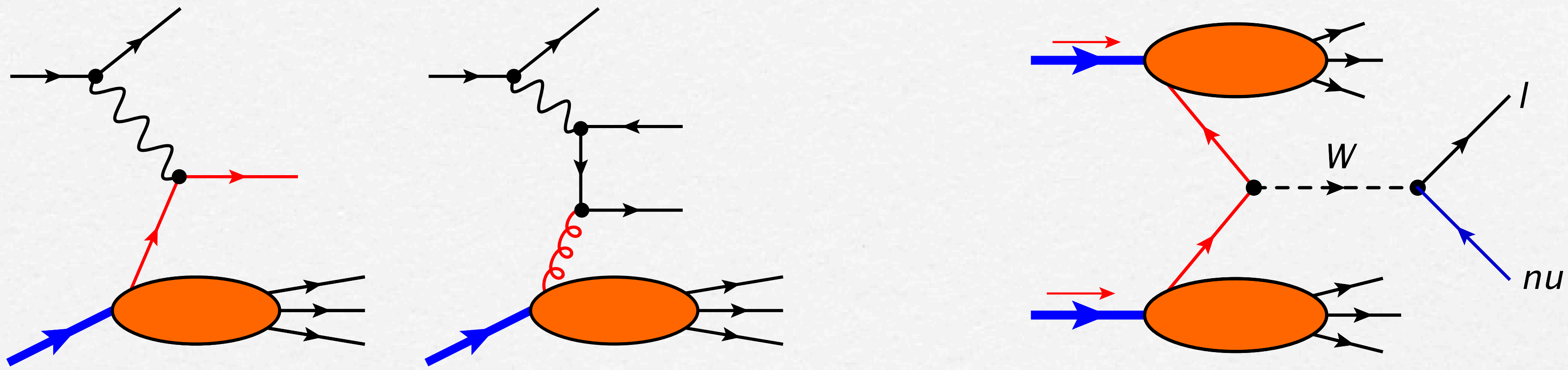

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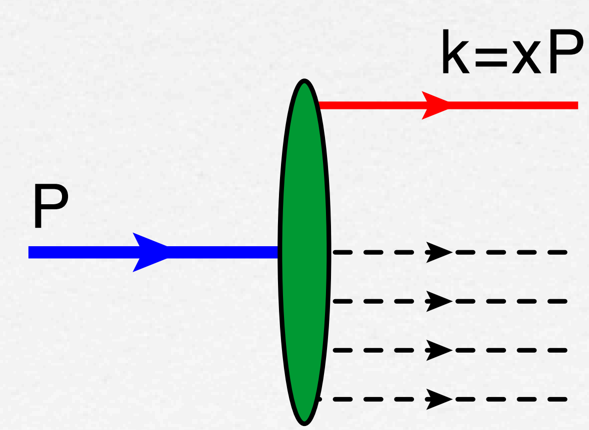
collinear parton distributions

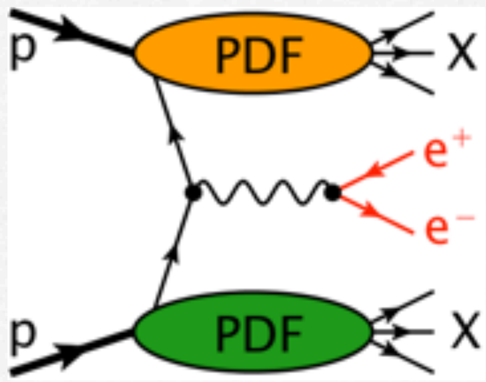
$$q(x,\mu) = \int \frac{d\lambda}{4\pi}\, e^{i\lambda x(P\cdot n)} \langle P|\bar{\psi}(0)\, \not{n}\, \mathcal{W}\, \psi(\lambda n)|P\rangle$$

$$G(x,\mu) = -\frac{1}{x(P\cdot n)} \int \frac{d\lambda}{2\pi}\, e^{i\lambda x(P\cdot n)} \langle P|F^{n\alpha}(0)\, \mathcal{W}\, F^{n}{}_{\alpha}(\lambda n)|P\rangle$$

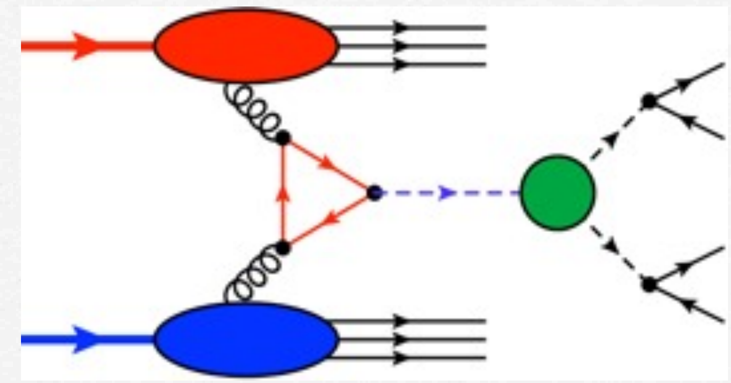


- Collinear factorization: 2 (or more...)-particle inclusive processes

Drell-Yan:



Higgs boson:



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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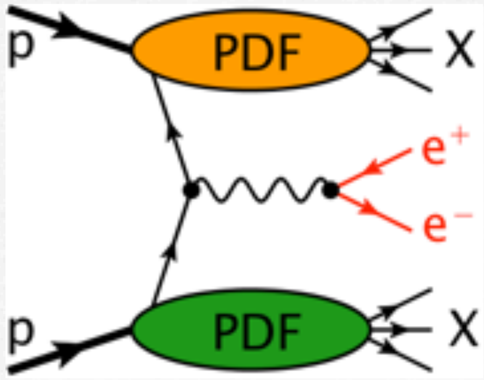
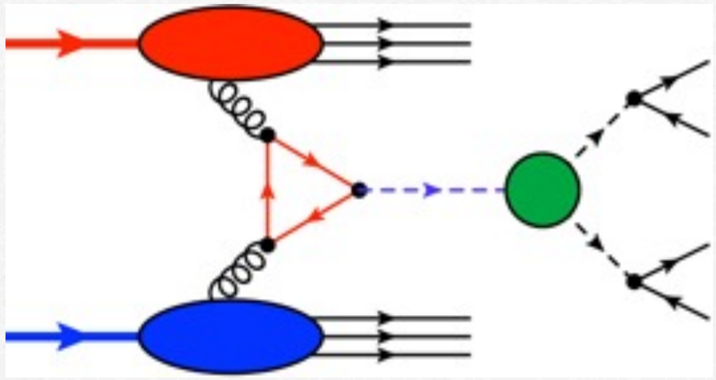
Drell-Yan: 

Higgs boson: 

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- q_T - dependence:

$$\boxed{\frac{d\sigma}{dq_T}(q_T \sim Q)}$$

one scale → collinear factorization ok,
transverse momentum generated perturbatively in hard part

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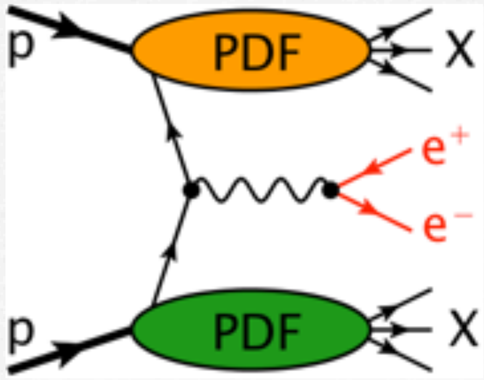

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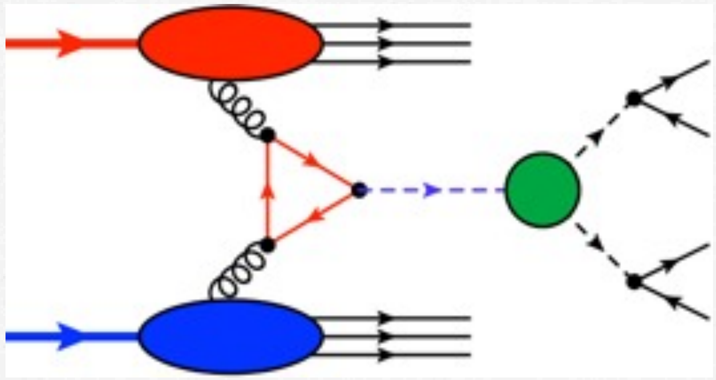

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$\frac{d\sigma}{dq_T}(\Lambda_{\rm QCD} \ll q_T \ll Q)$

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

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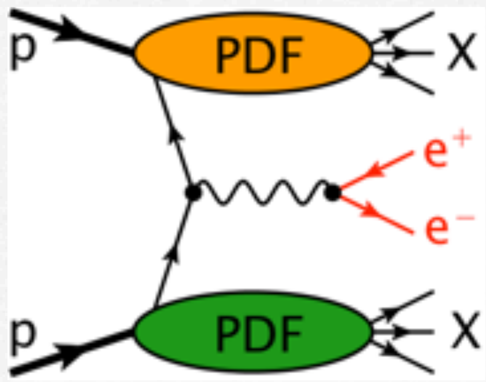

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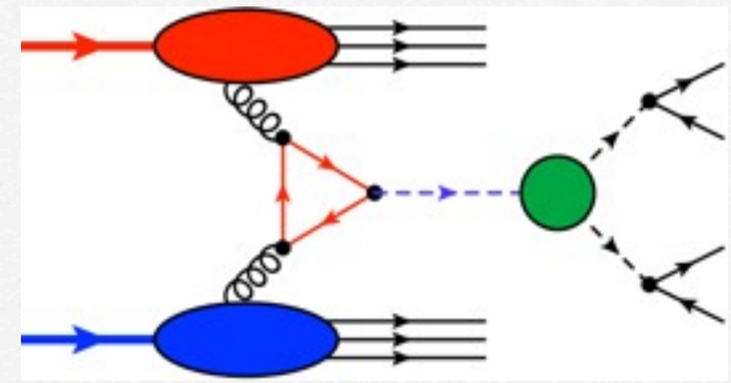

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→ CSS-resummation → coll. fact. still applicable

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

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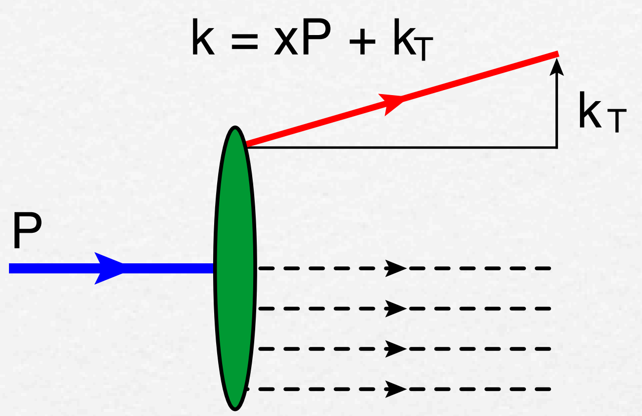
→ different kind of factorization

→ additional degree of freedom of partonic motion



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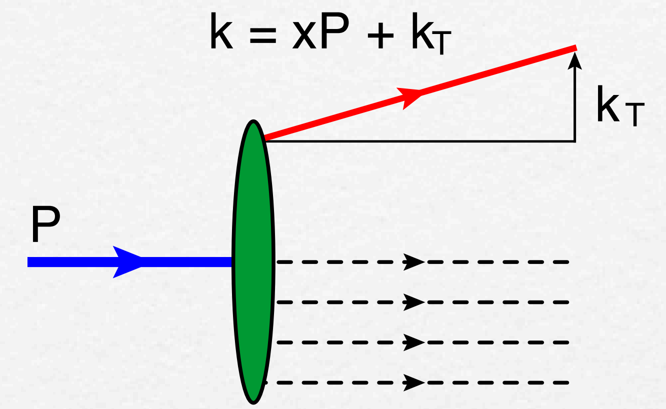
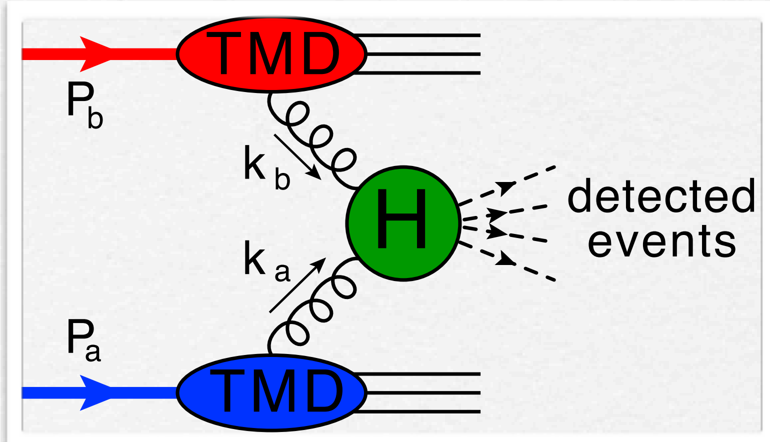


- TMD factorization theorem

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

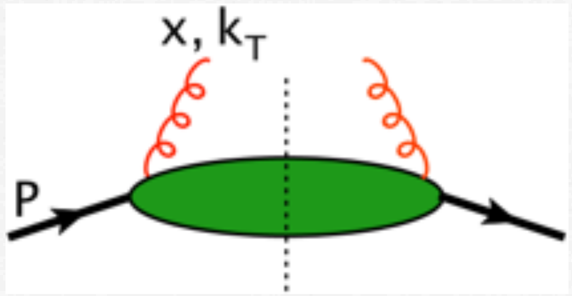


$$d\sigma \propto \mathrm{dPS}\, |H|^2 \int d^2k_{aT} \int d^2k_{bT}\ \delta^{(2)}(k_{aT} + k_{bT} - q_T)\ \Gamma(x_a, k_{aT})\ \Gamma(x_b, k_{bT})\ + \mathcal{O}(q_T/Q)$$

- proven for pp - collisions with color singlet final states

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

TMD gluonic matrix element



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

$\Gamma^{[T-even]}(x,\vec{k}_T)$			$\Gamma^{[T-odd]}(x,\vec{k}_T)$	
		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 → talk C. Pisano

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

* unpolarized gluons in transversely pol. proton: gluon Sivers function (T-odd)

$$\Gamma_T^{\alpha\beta}(x,k_T) = \frac{1}{2x}\left[g_T^{\alpha\beta}\frac{k_T \times S_T}{M}\ f_{1T}^{\perp g}(x,k_T^2) + \ldots\right]$$

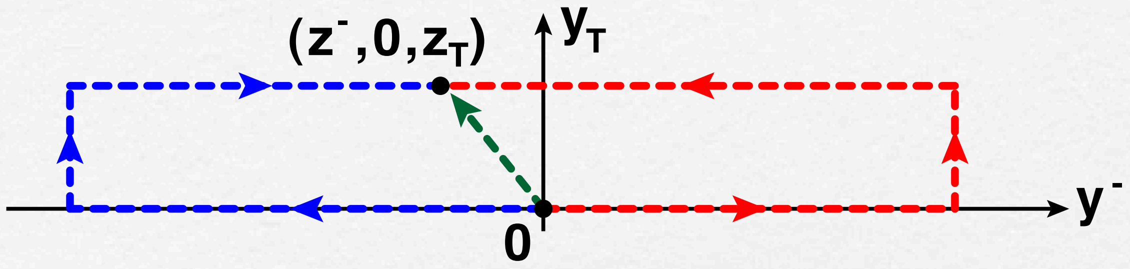
→ gluonic Spin - Orbit correlation

Wilson line for TMDs

Color Gauge invariant definition of TMDs ➞ Wilson line

$$\mathcal{W}[0;(0,z)] = \mathcal{P}\exp\left[-ig\int_0^z ds \cdot A(s)\right]$$

➞ Wilson line for TMD:
nontrivial, process dependent:



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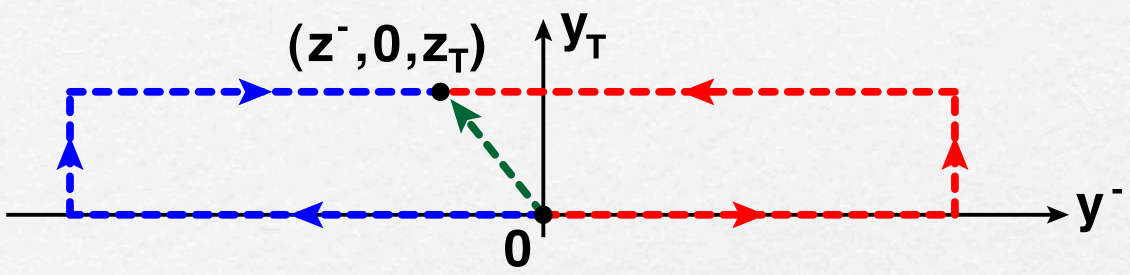
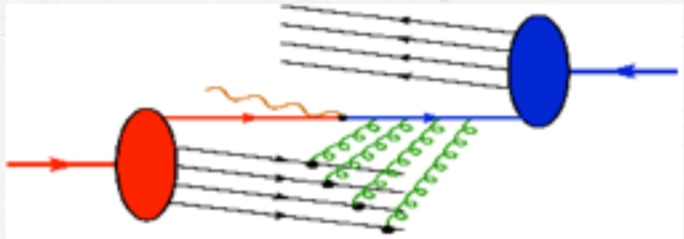
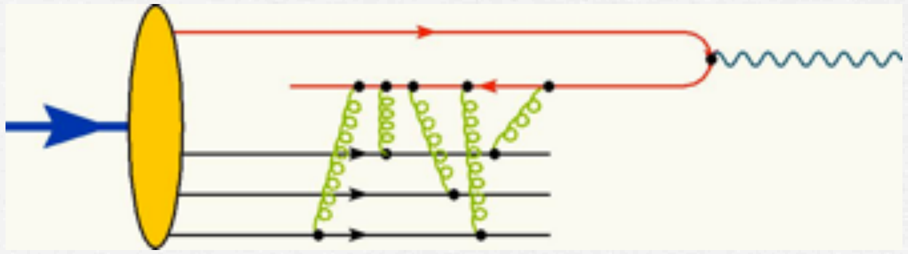


Initial State Interactions: pp ➝ color singlet + X



Final State Interactions: SIDIS



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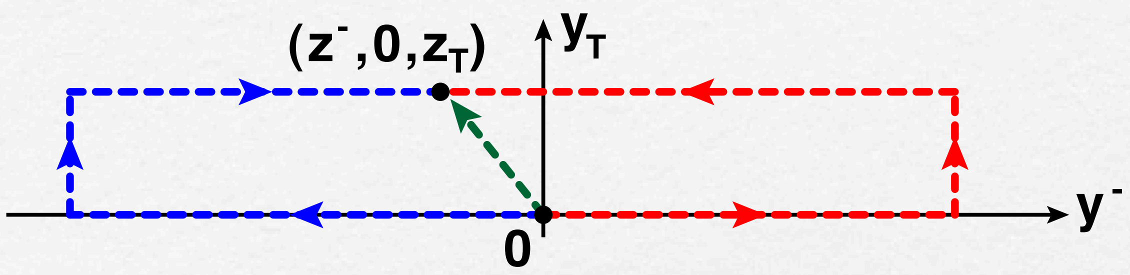

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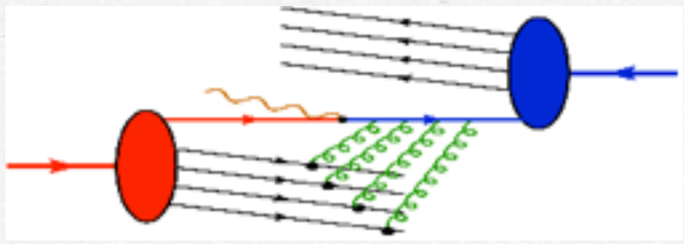

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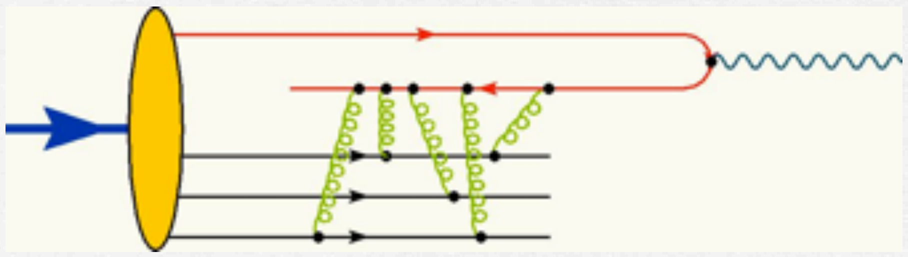

Time - reversal odd (T - odd) TMDs ➝ sign change

$$f_{1T}^{\perp g}(x,k_T^2)\Big|_{\mathrm{FSI}} = -f_{1T}^{\perp g}(x,k_T^2)\Big|_{\mathrm{ISI}}$$

“Color Entanglement”

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

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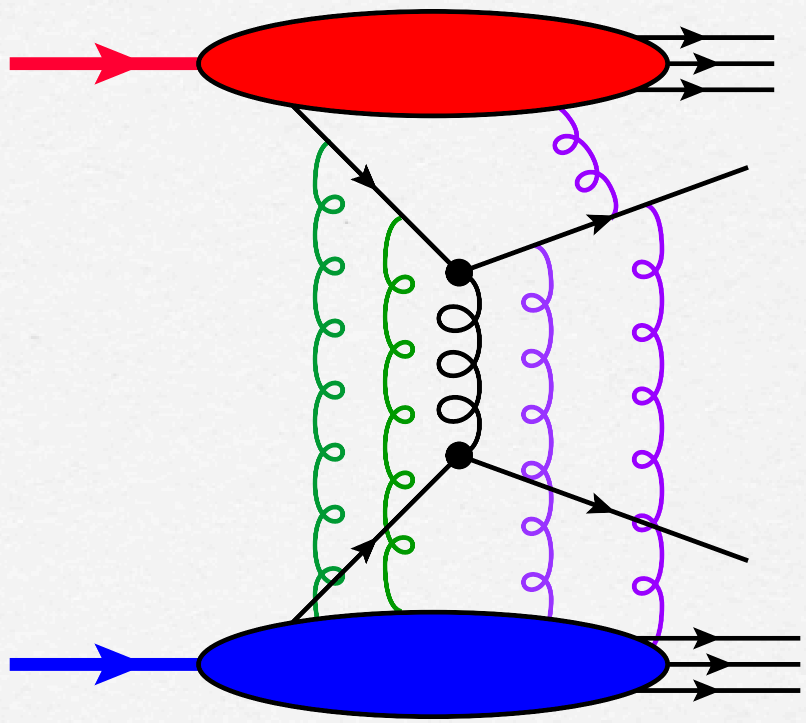

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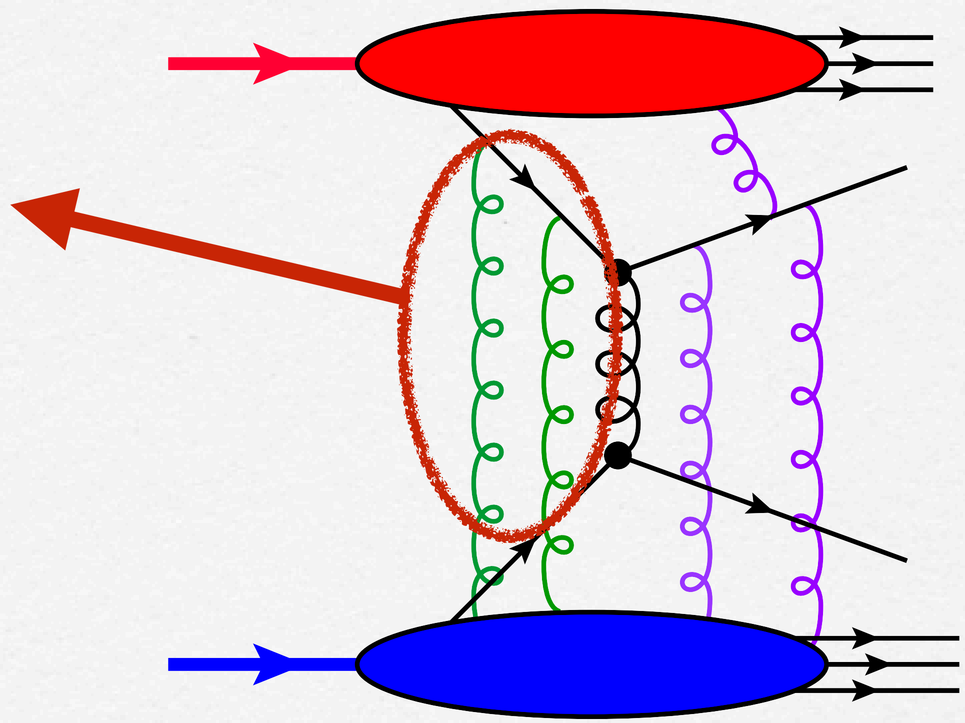

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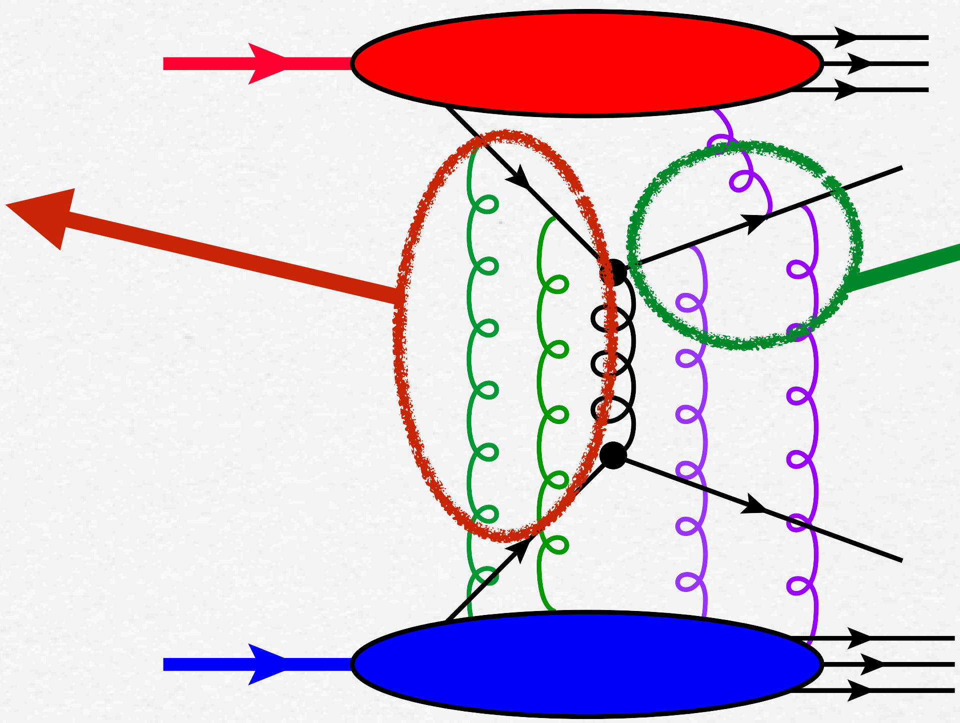

Final State Interactions from both nucleons are "entangled" in color space

→ cannot define Wilson lines

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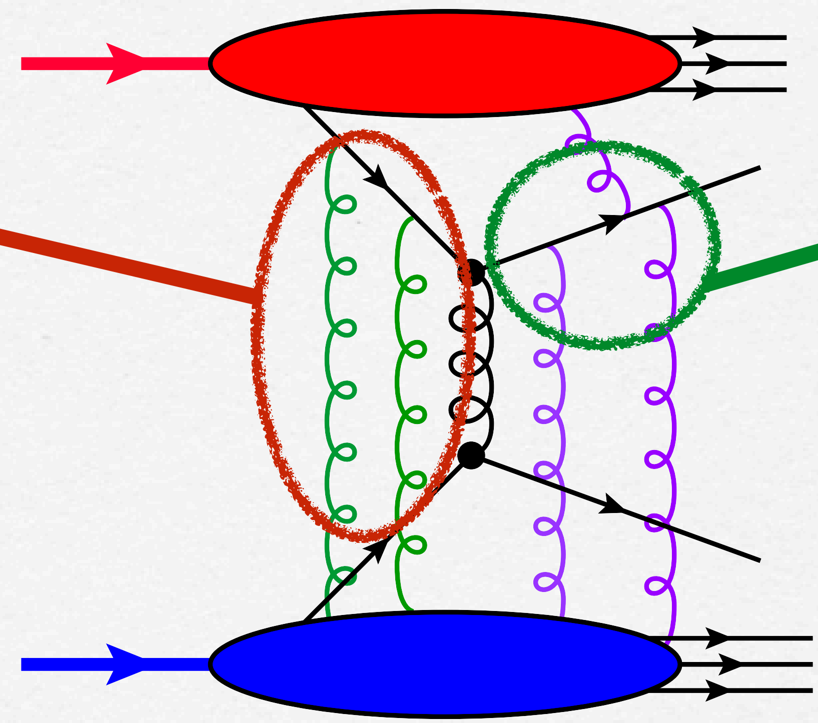

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TMD factorization in pp - collisions only for color singlet final states:

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

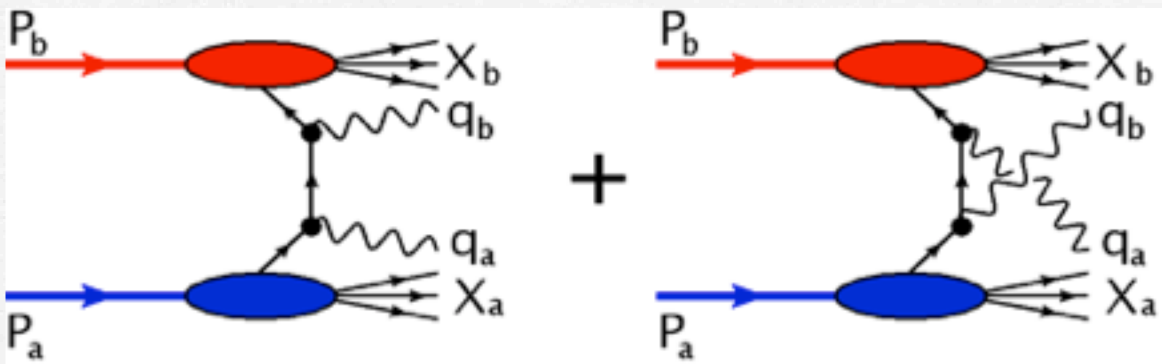
Gluon TMDs from SSAs in pp-collisions (AFTER, RHIC)

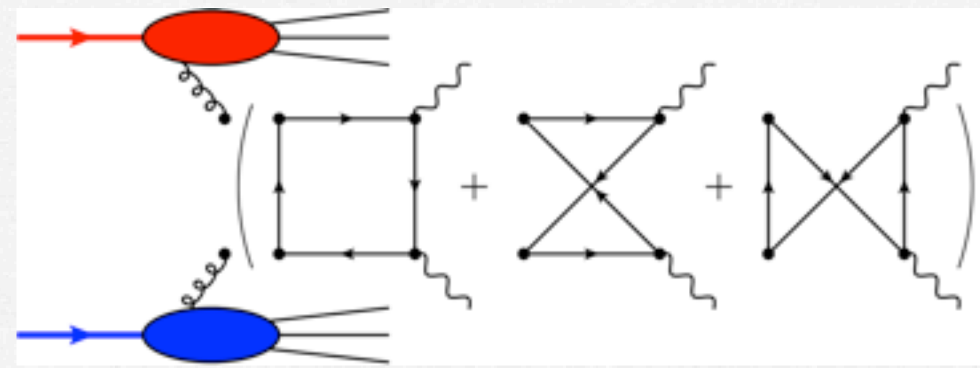
Photon Pair production

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

quark TMDs

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





- no colored final state ($\gamma\gamma$, γZ, ZZ) ⇒ TMD factorization ok
- contaminations from quark contributions:
- $\gamma\gamma$ - production: huge background from π^0 - decays, need isolated photons: isolation cuts
- γZ or ZZ - production: 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: $\eta : \; {}^1S_0^{(1)}$

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$^{2S+1}L_J$

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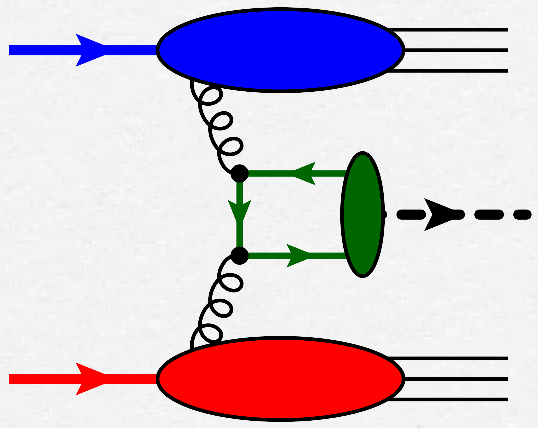

QQ - rest frame: non-relativistic approach

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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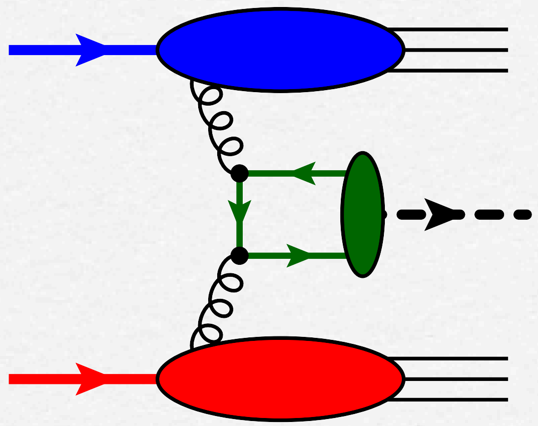

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TMD - formalism ($q_T \sim \Lambda$, $Q = M_Q$):

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

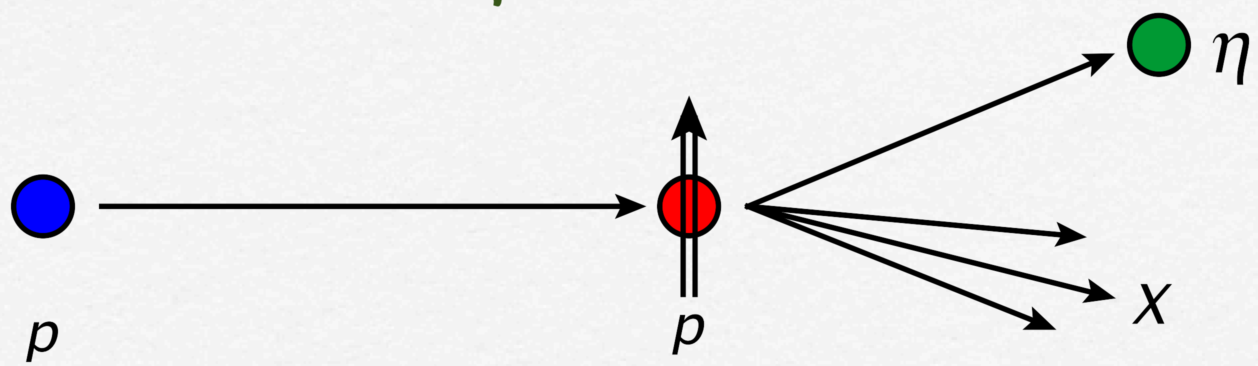
$$\frac{d\sigma(\chi_0)}{dy d^2q_T} = C_{\chi_0}([f_1^g \otimes f_1^g] + [h_1^g \otimes h_1^g])$$

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

- (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, difficult to implement isolation

SSA for isolated η-production

SSA at AFTER:



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$$A_{UL} = \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}} = 0$$

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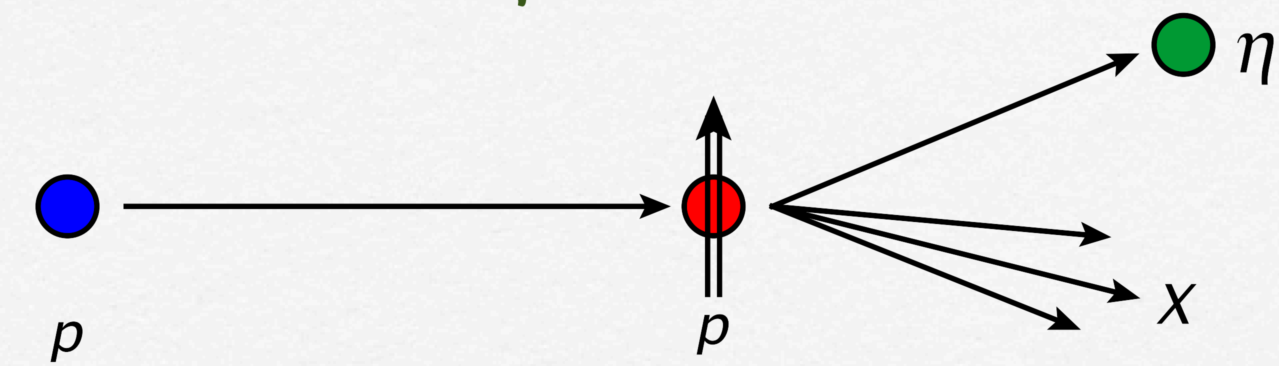

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gluon Sivers — gluon TMD Transversity — gluon "pretzelosity"

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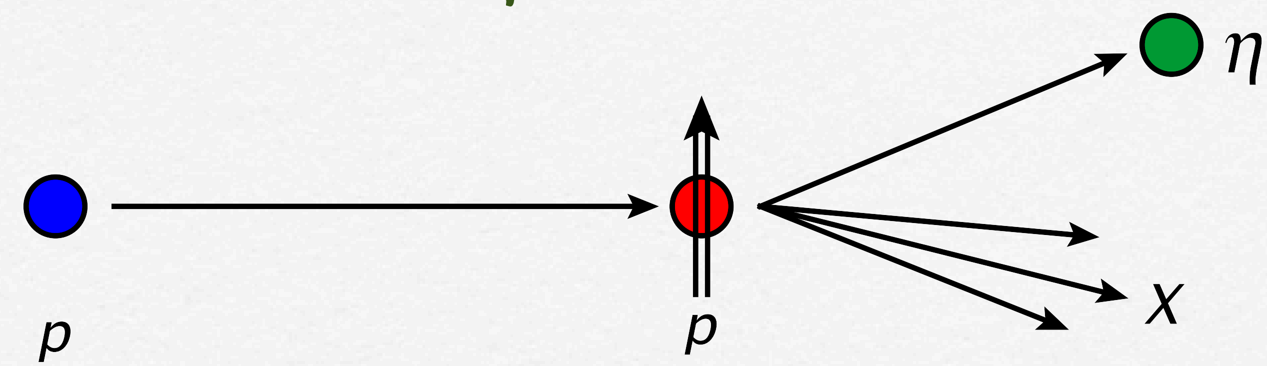

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gluon Sivers gluon TMD Transversity gluon "pretzelosity"

Transverse SSA at AFTER (in principle) sensitive to polarized gluon TMDs at large x!

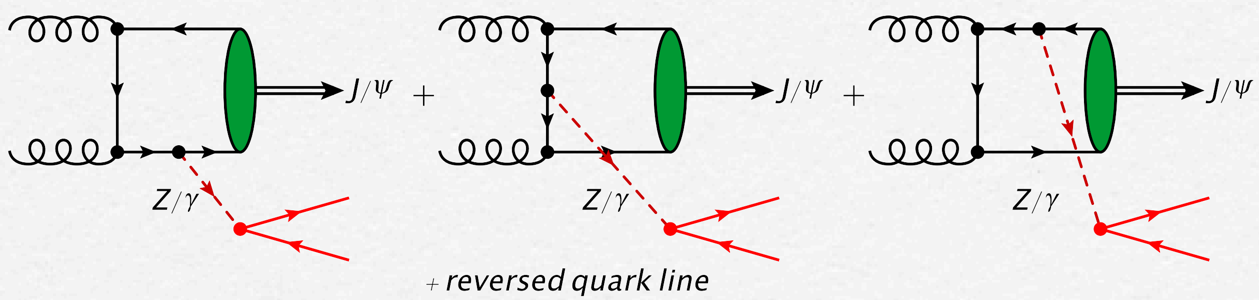
J/ψ + γ (μ⁺μ⁻) - production

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

➙ less statistics, but more kinematic "freedom"...

➙ J/ψ+γ: both J/ψ and photon need to be isolated;

J/ψ + dilepton: only isolation for J/ψ, but Cross Section much reduced...



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J/ψ + γ (μ⁺μ⁻) - production

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

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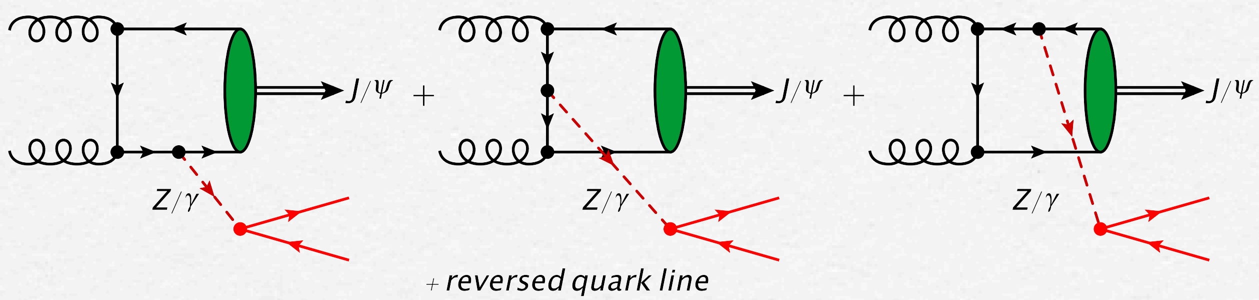

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\end{aligned}
$$

TMD result at $q_T \ll Q$

$$
\begin{aligned}
\frac{d\sigma_{UU}^{qq\to J/\psi(\mu^+\mu^-)}}{dY\, dQ\, d^2q_T\, dM_B^2\, d\Omega} =\; & \hat{F}_1(Q, \cos\theta, M_B^2)\, [f_1^g \otimes f_1^g] + \hat{F}_2(Q, \cos\theta, M_B^2)\, [h_1^{\perp g} \otimes h_1^{\perp g}] \\
& + \hat{F}_3(Q, \cos\theta, M_B^2) \cos(2\phi)\, ([f_1^g \otimes h_1^{\perp g}] + \{x_a \leftrightarrow x_b\}) \\
& + \hat{F}_4(Q, \cos\theta, M_B^2)\, \cos(4\phi)\, [h_1^{\perp g} \otimes h_1^{\perp g}] + \mathcal{O}(q_T/Q)
\end{aligned}
$$

- Factors F_1, F_2, F_3, F_4 perturbatively at LO ➙ NLO: future work…
- J/ψ + γ: $F_2 = 0$ ➙ pure $f_1{}^g$ - extraction from q_T - distribution possible
- 2-particle final state: azimuthal cos(2ϕ) and cos(4ϕ) - modulation

➙ talk C. Pisano

SSA in isolated J/ψ + γ [μ+μ-] - production

Long. Pol. Target:

$$\begin{aligned}\Delta\sigma_{UL} &\equiv d\sigma^{\rightarrow} - d\sigma^{\leftarrow} \\ &= \hat{F}_3(Q, \cos\theta, M_B^2)\,\sin(2\phi)\,[f_1^g \otimes h_{1L}^{\perp g}] \\ &\quad + \hat{F}_4(Q, \cos\theta, M_B^2)\,\sin(4\phi)\,[h_1^{\perp g} \otimes h_{1L}^{\perp g}]\end{aligned}$$

gluonic "wormgear" function:

lin. pol. gluons in long. pol. proton (T-odd)

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&\quad + \sin(2\phi)\ \{...\} + \sin(4\phi)\ \{...\}\Big] + \cos\phi_s \Big[\sin(2\phi)\ \{...\} + \sin(4\phi)\ \{...\}\Big]
\end{aligned}
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SSA in isolated J/ψ + γ [$\mu^+\mu^-$] - production

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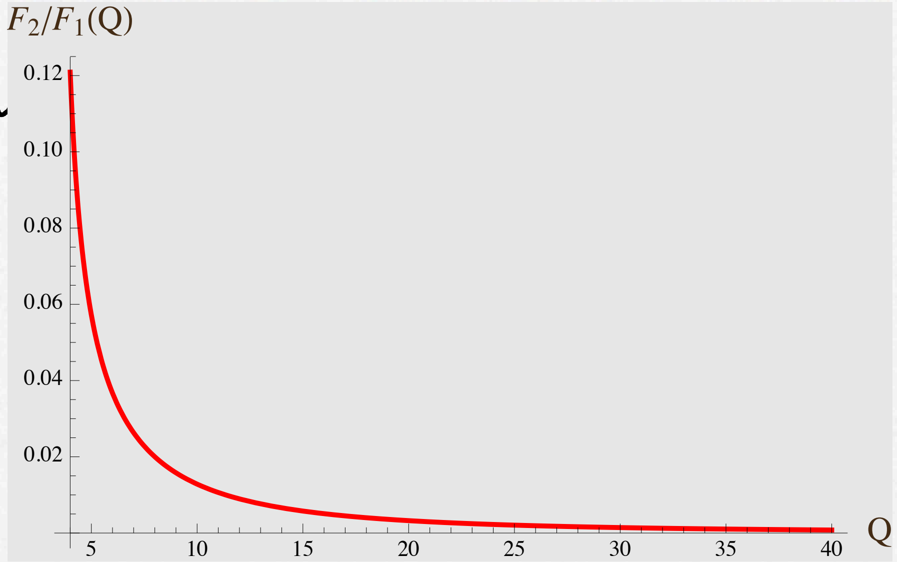
Sivers effect ➞ sufficient to integrate out CS - angles θ and ϕ [and dilepton mass M_B^2]

$$\begin{aligned}A_{UT}(Y, Q, q_T) &= \frac{\int d\Omega\ dM_B^2\ (d\sigma^{\uparrow} - d\sigma^{\downarrow})}{\int d\Omega\ dM_B^2\ (d\sigma^{\uparrow} + d\sigma^{\downarrow})} \\ &= \sin\phi_s \left[\frac{[f_1^g \otimes f_{1T}^{\perp g}] - \beta(Q)\ ([h_1^{\perp g} \otimes h_1^g] + [h_1^{\perp g} \otimes h_{1T}^{\perp g}])}{[f_1^g \otimes f_1^g] + \beta(Q)[h_1^{\perp g} \otimes h_1^{\perp g}]}\right]\end{aligned}$$

- perturbative factor β very small for J/ψ + $\mu^+\mu^-$ - production
- even identical to zero for J/ψ + γ - production

$$\boxed{\beta(Q) = \frac{\int d(\cos\theta) dM_B^2 \;\hat{F}_2(Q,\cos\theta,M_B^2)}{\int d(\cos\theta) dM_B^2 \;\hat{F}_1(Q,\cos\theta,M_B^2)}}$$



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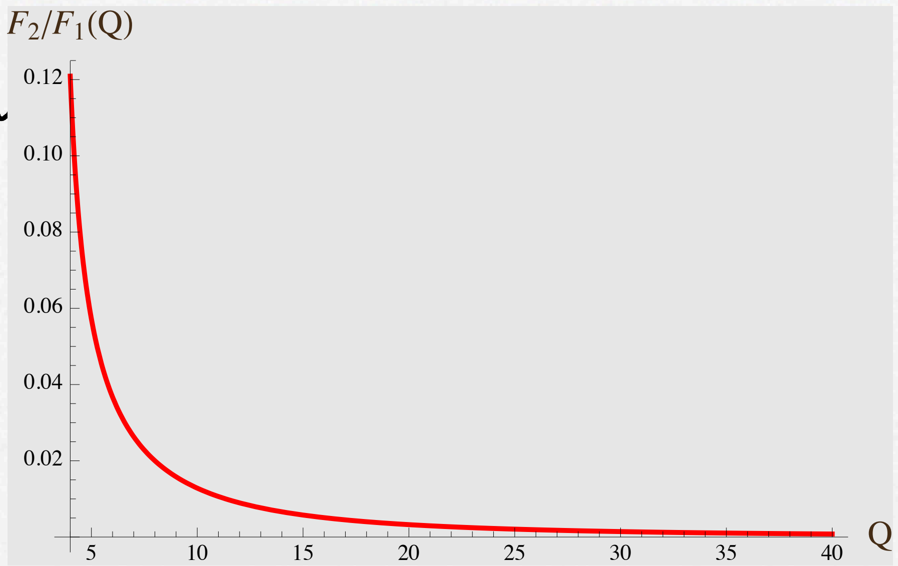

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- Hence, we can approximate the SSA:

$$A_{UT}(Y, Q, q_T) \simeq \sin\phi_s \frac{[f_1^g \otimes f_{1T}^{\perp g}]}{[f_1^g \otimes f_1^g]}$$

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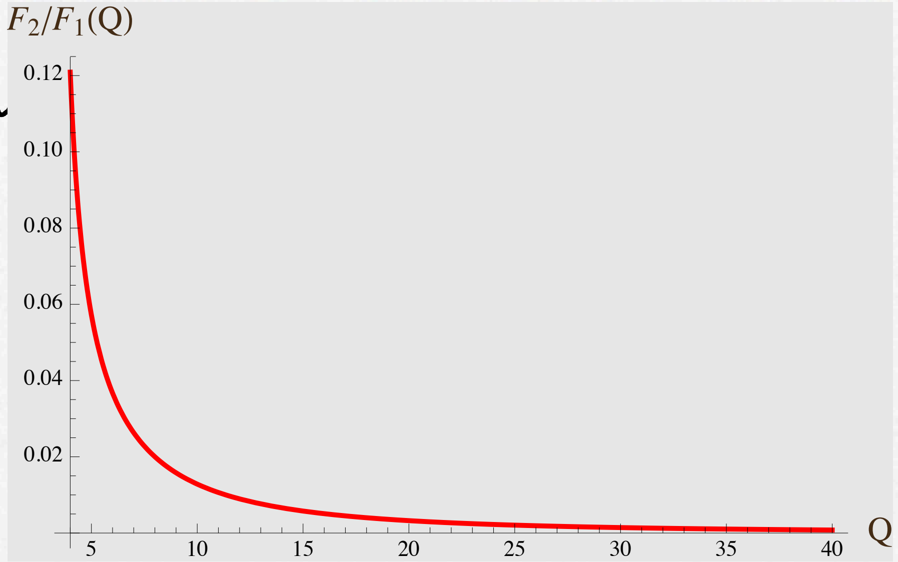

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Numerical estimates

Not much experimental information on Gluon TMDs → models, ...

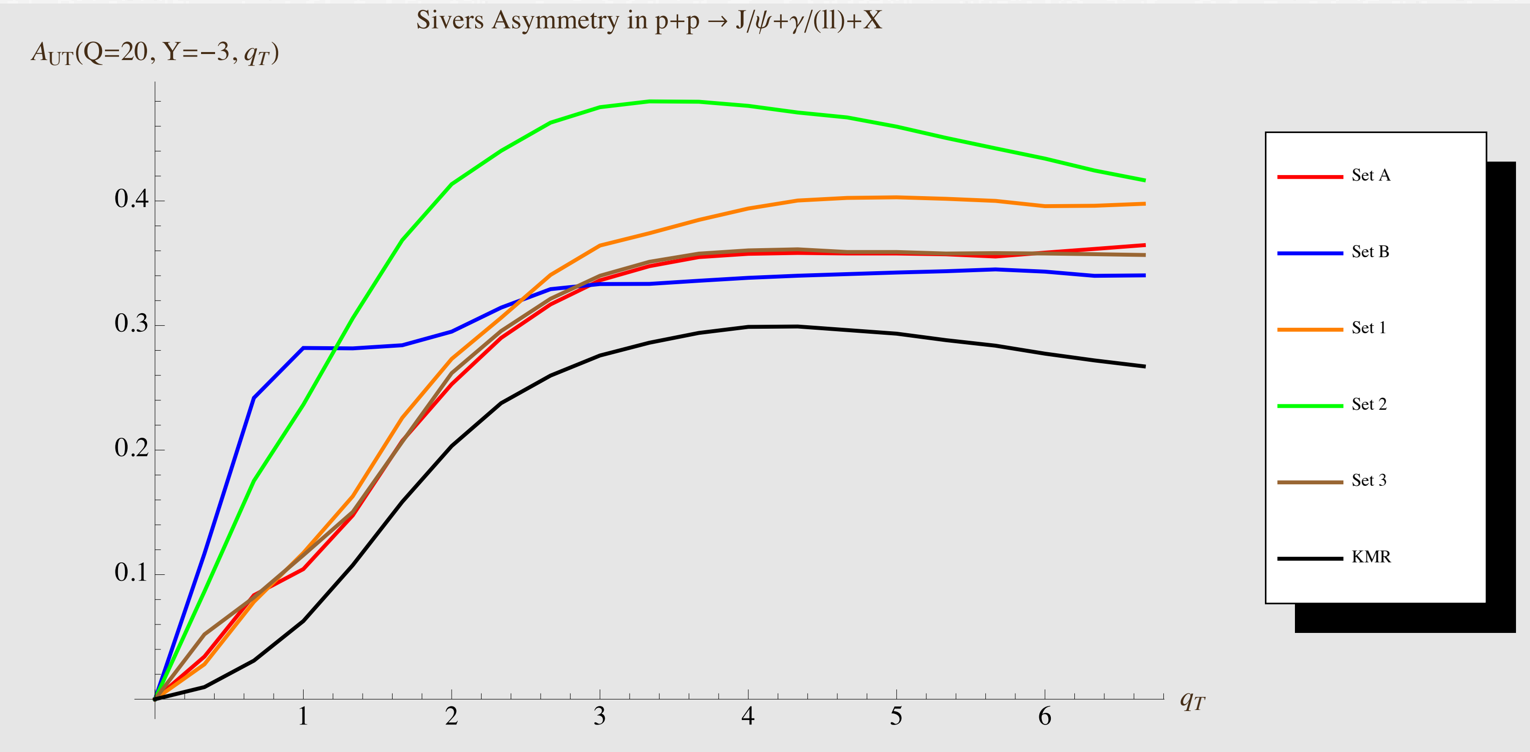
Our approach: Link the unpolarized gluon TMD to "unintegrated parton distribution" used in small-x physics (parameterizations to HERA data)

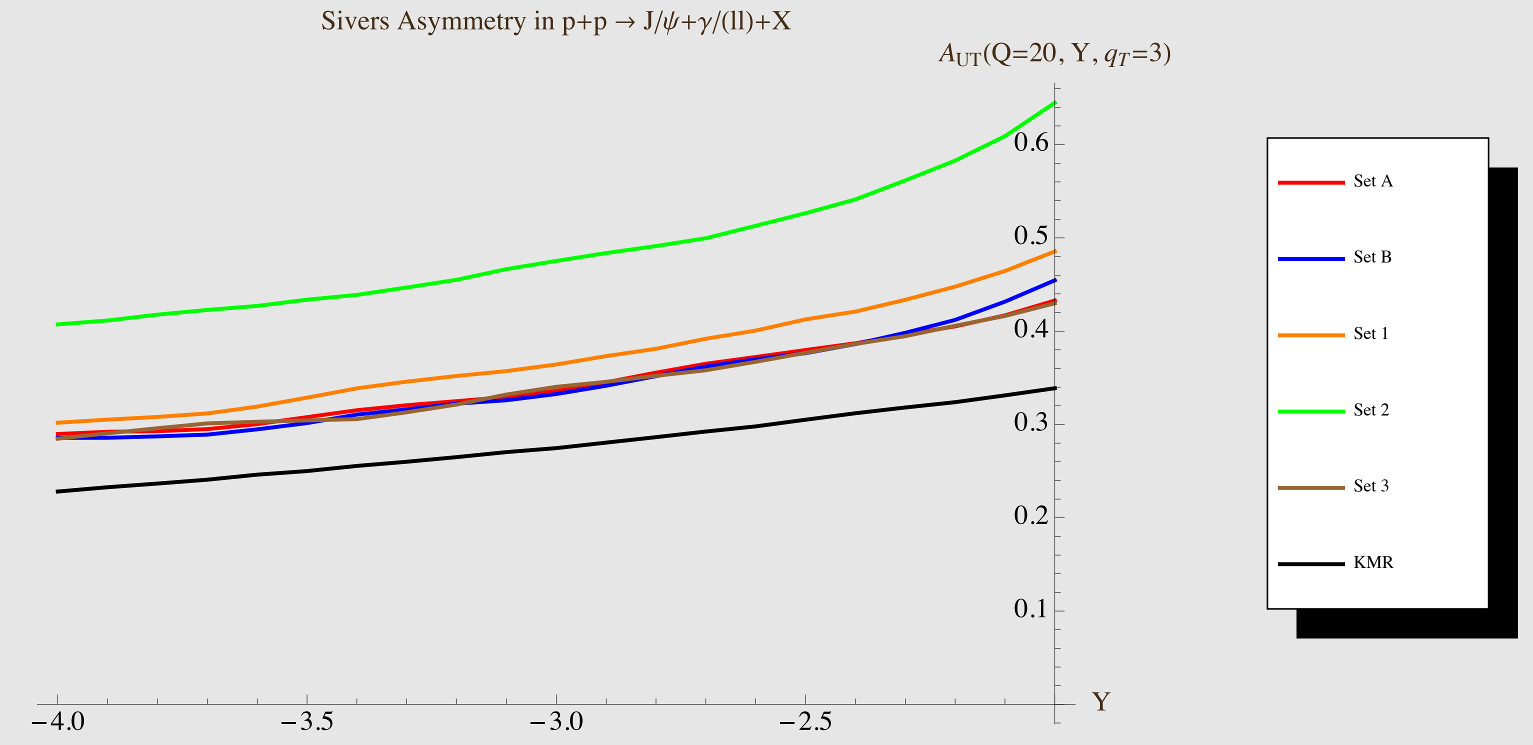
$$f_1^g(x, k_T) \leftrightarrow \mathrm{uPDF}(x, k_T)$$

Gluon Sivers function: Assume saturation of positivity bound
→ upper bounds for SSA

$$f_{1T}^{\perp g}(x, k_T) \leq \frac{M}{k_T} f_1^g(x, k_T)$$

Upper bounds for gluon Sivers asymmetry





Bounds given in AFTER kinematics

$$\sqrt{S} \simeq 120 \text{ GeV}; \;\; Y \simeq -4 \text{ to } -2$$

Saturated bounds:
large effects are predicted
SSA = 30% - 40%

even if the Sivers function is
"undersaturated" by a factor 1/100
➙ still an effect of about 0.3%

Bounds remain sizeable
at large negative pair rapidities:
$x_a \ll 1; \, x_b \to 1$

Summary

- Isolated Quarkonium observables give unique insight into the gluonic structure of the nucleon
- Quarkonium production in combination with TMD factorization: 3-dim momentum picture of (polarized) gluons in the nucleon
- Transverse SSAs at AFTER → gluon Sivers effect feasible!

Backup slides

Relations to collinear Parton Densities

"naive" relation through k_T - integration:

$$\int d^2 k_T \ f_1^{q/g}(x, k_T^2) = f_1^{q/g}(x)$$

$$G_F(x,x) = \frac{\pi}{2} f_{1T}^{\perp(1)}(x) = \int d^2 k_T \ \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2)$$

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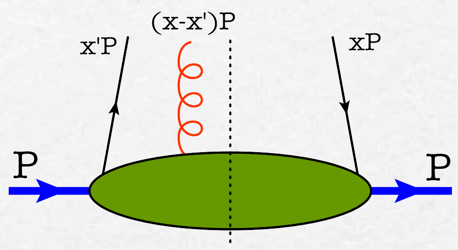
Quark-Gluon Correlation Functions

(ETQS-matrix element)



$$\frac{M}{2}\epsilon_T^{\alpha\beta} S_{T\beta}\, G_F^q(x,x') = \int \frac{d\lambda\, d\eta}{2(2\pi)^2}\, e^{i(P\cdot n)(x'\lambda+(x-x')\eta)} \langle P,S_T|\bar{q}(0)\gamma^+\, gF^{+\alpha}(\eta n)\, q(\lambda n)|P,S_T\rangle$$

→ Relations work when applying collinear factorization (leading twist, higher twist)

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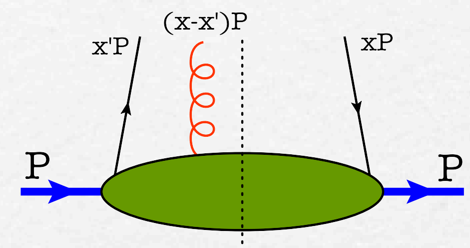

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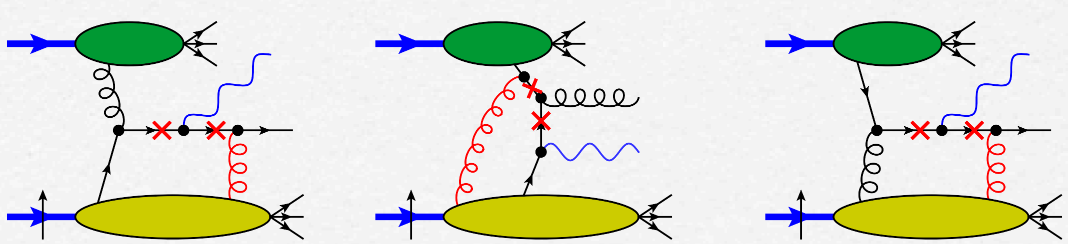
Example: Collinear Twist-3 factorization for SSA in pp → γX

[Qiu, Sterman; Kouvaris, Vogelsang, Yuan, Koike, Yoshida, ...]



$$E\frac{d\Delta\sigma}{d^3q_\gamma} \propto \int \frac{dx'}{x'} \int \frac{dx}{x}\, f_1^{q/g}(x')\, [G_F^{q/g}(x,x) - x\tfrac{d}{dx}G_F^{q/g}(x,x)]\, \hat{H}^{SGP}(x,x') + \ldots$$

Correct, full definition of TMDs a la Collins, etc.

Relation to collinear Densities through

"perturbative tail" of TMDs (= large k_T behavior)

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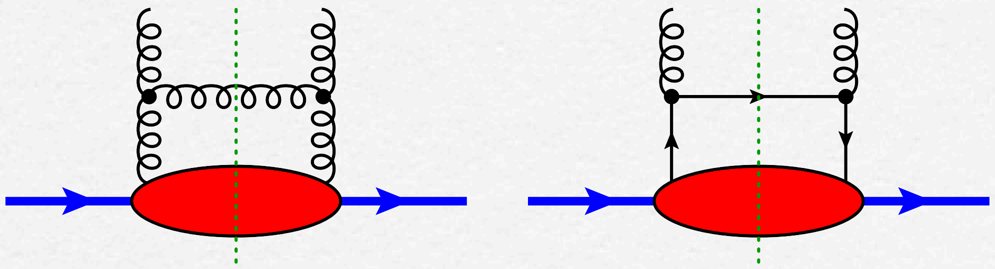
large transverse momentum behaviour of TMD → perturbative calculation:



$$f_1^g(x, p_T^2 \gg \Lambda^2) \propto \frac{\alpha_s}{p_T^2} \sum_{i=q,g} \int_x^1 \frac{dz}{z} \mathcal{C}_{ig}(z, \zeta/p_T^2)\; f_1^i(x/z, \mu) + \mathcal{O}(\alpha_s^2)$$

$$h_1^{\perp g}(x, p_T^2 \gg \Lambda^2) \propto \frac{\alpha_s}{p_T^4} \sum_{i=q,g} \int_x^1 \frac{dz}{z}\; \frac{1-z}{z}\; f_1^i(x/z, \mu) + \mathcal{O}(\alpha_s^2)$$

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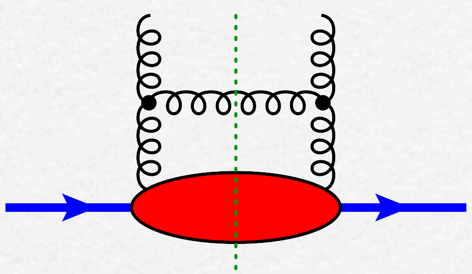

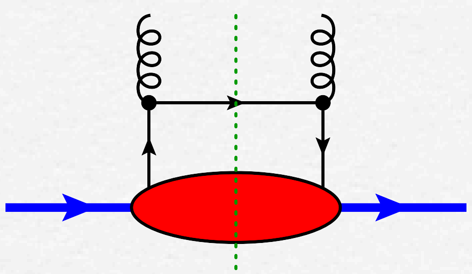

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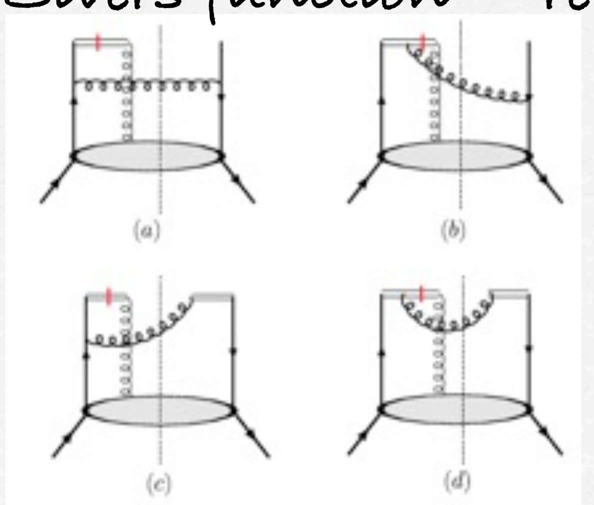
Sivers function → relation to Quark-Gluon correlations at large k_T



$$f_{1T}^{\perp q}(x, p_T^2 \gg \Lambda^2) \quad \propto \quad \frac{\alpha_s}{p_T^4} \int_x^1 \frac{dz}{z} \Big[C_1^{\mathrm{SGP}}\; G_F(\tfrac{x}{z}, \tfrac{x}{z}) + C_2^{\mathrm{SGP}}\; (\tfrac{d}{dx} G_F)(\tfrac{x}{z}, \tfrac{x}{z}) + C_1^{\mathrm{HFP}}\; G_F(\tfrac{x}{z}, x) \Big]$$

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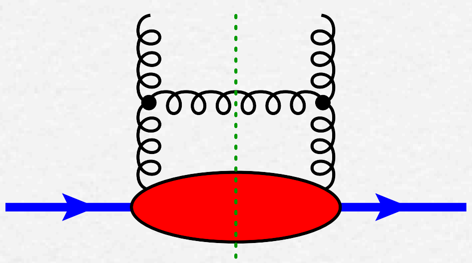

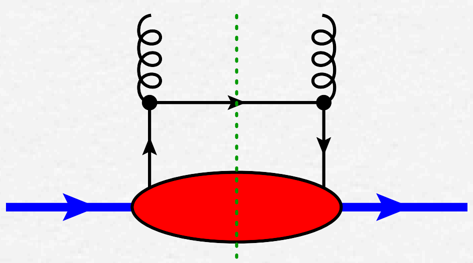

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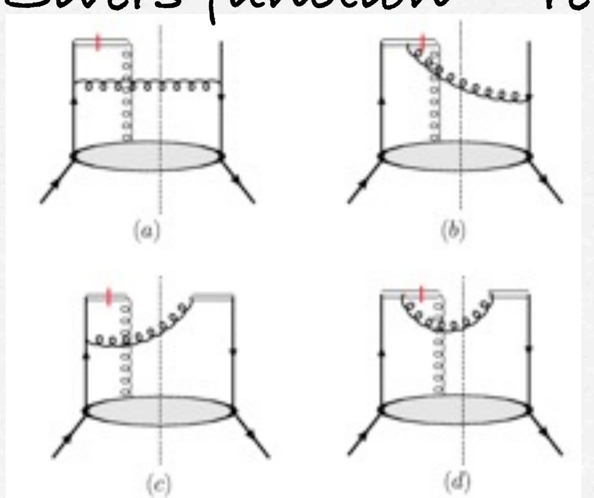

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→ "TMD fact. = Collinear fact."

in overlapping region $\Lambda \ll q_T \ll Q$ in DY/SIDIS

[Ji, Qiu, Vogelsang, Yuan]

Why (transverse) SSA?

Two important experimental observations for TSSAs

$$A_N = A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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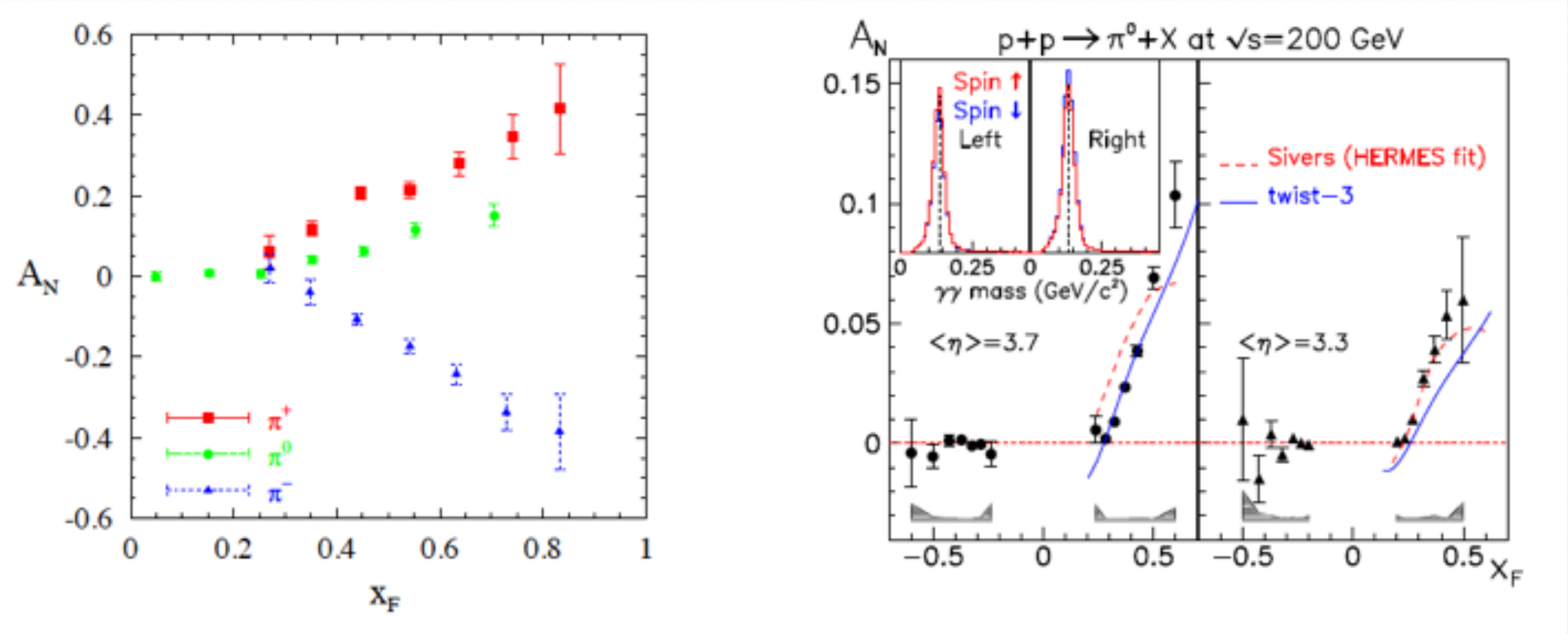
$$A_N = A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

1) Transverse SSA in pion-production $\quad p + p^{\uparrow} \to \pi + X$



$\sqrt{s} = 20$ GeV [*E704 coll. (1991)*] $\quad \sqrt{s} = 200$ GeV [*STAR coll. (2008)*]

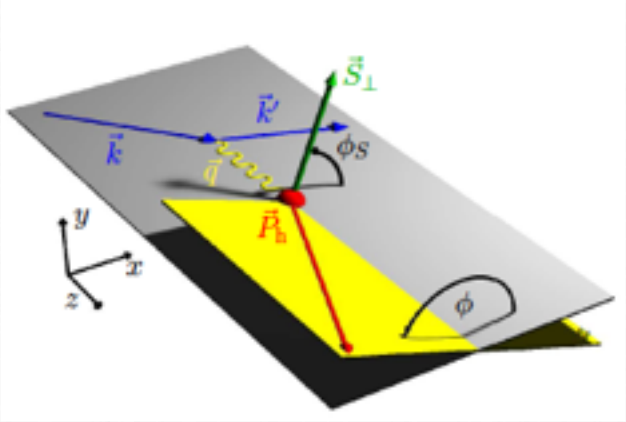
- sizeable effect at large x_F (and large P_T... (?))
- cannot be explained in the naive parton model [Kane, Repko]

→ collinear twist-3 framework / not fully understood to the present day

2) Transverse SSA in semi-inclusive DIS

$e + p^{\uparrow} \to e + \pi + X$

("Sivers", "Collins" effect...)



$$d\sigma_{UT}^{\text{SIDIS}} = F_{UT}^{\sin(\phi-\phi_S)} \sin(\phi - \phi_S) + F_{UT}^{\sin(\phi+\phi_S)} \sin(\phi + \phi_S) + \ldots$$

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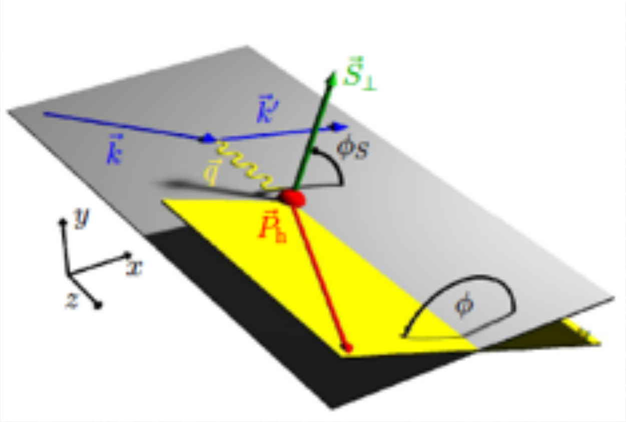

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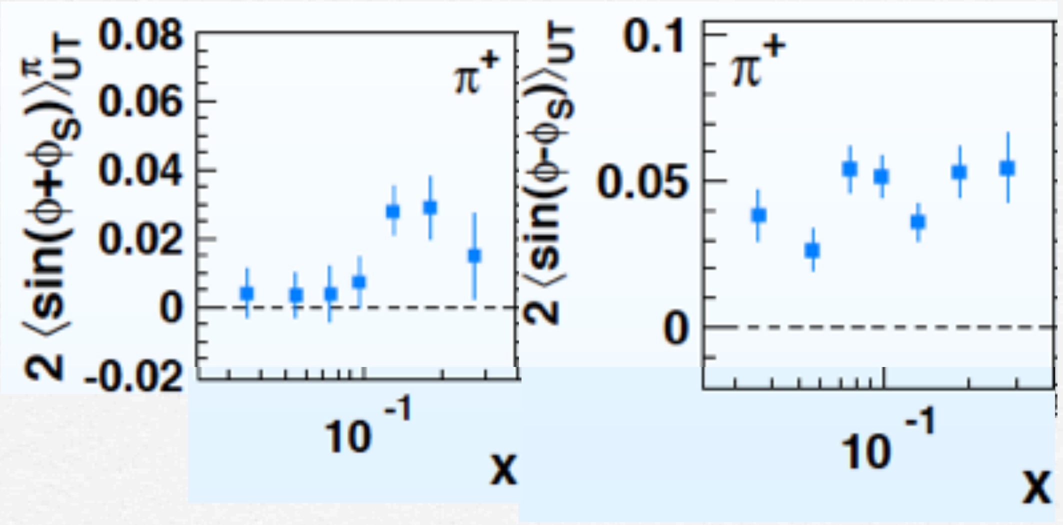
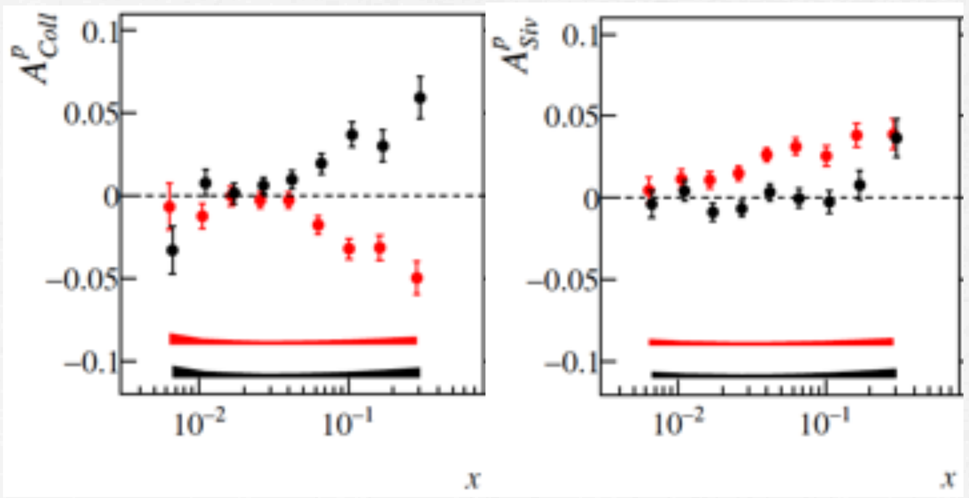
HERMES:



COMPASS:



- Effect on the percent-level
- usually discussed in TMD-framework