TMDs in quarkonia production

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Polarization measurements in *ee*, *ep*, *pp* and heavy-ion collisions

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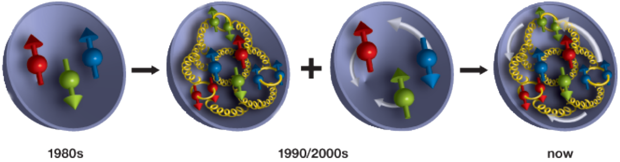
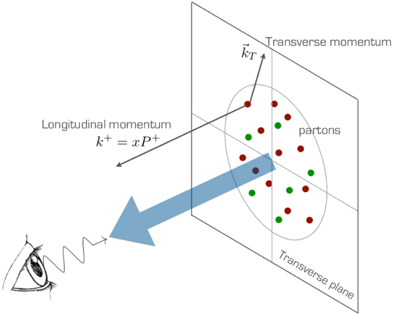
Outline

1. Introduction
2. TMDs & quarkonia in unpolarized collisions
3. TMDs & quarkonia in polarized collisions
4. Conclusions

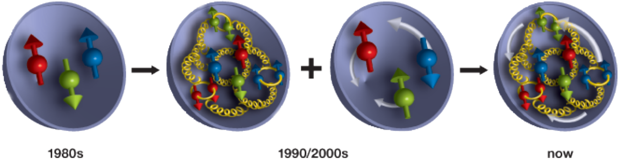
1. Introduction

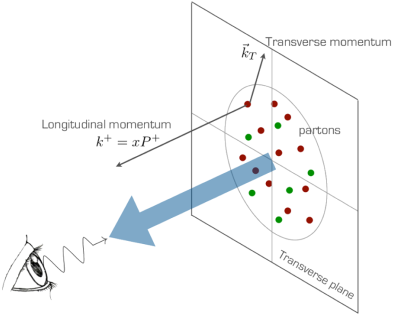
3D nucleon structure and TMDs





3D nucleon structure and TMDs





- collinear QCD at leading twist fails in explaining transverse polarization phenomena in high energy processes [E.Niel & A.Vossen talks]

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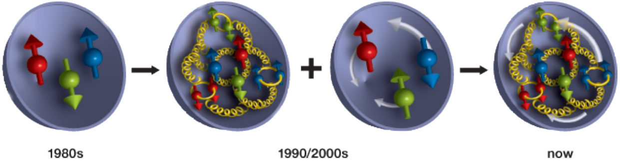

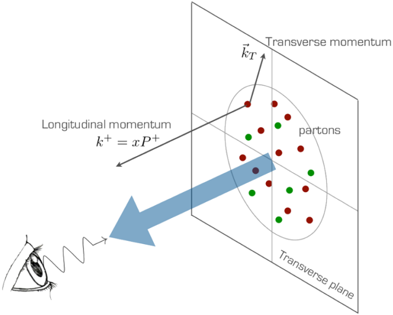

- collinear QCD at leading twist fails in explaining transverse polarization phenomena in high energy processes [E.Niel & A.Vossen talks]
- a plethora of 3D distributions has been introduced, *e.g.* TMDs, GPDs [C.Van Hulse & P.Sznaider talks]

Gluon TMD distributions

- 8 independent gluon TMD distributions

N \ g	U	Circular	Linear
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_1^g, $h_{1T}^{\perp g}$

Time-reversal even Time-reversal odd
Non-zero in the collinear limit

- some of them are related to each other by positivity bounds
- Initial- (ISI) and Final-State Interactions (FSI) can make TMDs process dependent

TMD physics in a nutshell

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  matching region: $q_T \sim Q$;
- QCD evolution equation $\neq$ usual DGLAP evolution

$2 \to 2$ vs $2 \to 1$ processes

- $2 \to 1$ processes:

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  - Hard scale can only be the mass of the particle $Q^2 = M^2$
    $\longrightarrow$ fixed scale, not helpful for TMD evolution studies
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- Back-to-back (low q_T) $2 \to 2$ processes:
  - produced quarkonia can have both large $\mathbf{p}_T$, with small $\mathbf{q}_T = \mathbf{p}_{\mathcal{Q}_1,T} + \mathbf{p}_{\mathcal{Q}_2,T}$. $|\mathbf{p}_T|$ can be tuned to large enough values to be detectable
  - This renders the TMD region ($q_T << Q$) virtually as wide as desired
  - Hard scale is $Q^2 = (p_{\mathcal{Q}_1} + p_{\mathcal{Q}_2})^2$: can be tuned for TMD evolution studies
  - Drawback: Double Parton Scattering (DPS) can be not negligible
    [Lansberg, Shao JHEP 1610 (2016) 153, NPB 900 (2015) 273, PLB 751 (2015) 479]

2. TMDs & quarkonia in unpolarized collisions

Low P_T quarkonia and TMDs

[From J.-P. Lansberg]

PHYSICAL REVIEW D **86**, 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

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Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

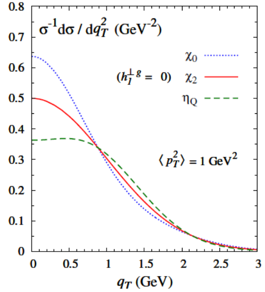
- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- In general, heavy-flavor prod. selects out gg channels
- Affect the low P_T spectra:

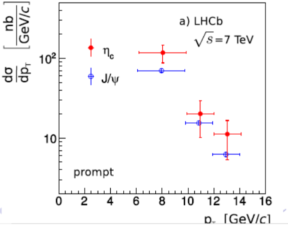
$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2) \ \& \ \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$$

$$\left(R = \frac{\mathcal{C}[w_0^{hh}\, h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]}\right)$$

- Cannot tune Q: $Q \simeq m_Q$
- Low P_T: Experimentally very difficult

First η_c production study at collider ever, only released in 2014 for $P_T^{\eta_c} > 6$ GeV **LHCb, EPJC75 (2015) 311**





gg fusion in arbitrary unpolarized process

$$d\sigma^{gg} \propto \overbrace{\left(\sum_{\lambda_a,\lambda_b} \hat{\mathcal{M}}_{\lambda_a,\lambda_b}\hat{\mathcal{M}}^*_{\lambda_a,\lambda_b}\right)}^{F_1} \mathcal{C}[f_1^g f_1^g]$$

$\Rightarrow$ helicity non-flip, azimuthally independent

$$+\overbrace{\left(\sum_{\lambda} \hat{\mathcal{M}}_{\lambda,\lambda}\hat{\mathcal{M}}^*_{-\lambda,-\lambda}\right)}^{F_2} \mathcal{C}[w_2 \times h_1^{\perp g} h_1^{\perp g}]$$

$\Rightarrow$ double helicity flip, azimuthally independent

$$+\overbrace{\left(\sum_{\lambda_a,\lambda_b} \hat{\mathcal{M}}_{\lambda_a,\lambda_b}\hat{\mathcal{M}}^*_{-\lambda_a,\lambda_b}\right)}^{F_3} \mathcal{C}[w_3 \times f_1^g h_1^{\perp g}]$$

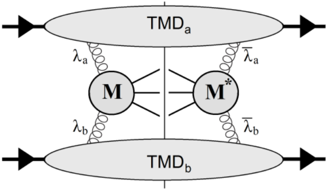
$+\{a \leftrightarrow b\}$

$\Rightarrow$ single helicity flip, $\cos(2\phi)$-modulation

$$+\overbrace{\left(\sum_{\lambda} \hat{\mathcal{M}}_{\lambda,-\lambda}\hat{\mathcal{M}}^*_{-\lambda,\lambda}\right)}^{F_4} \mathcal{C}[w_4 \times h_1^{\perp g} h_1^{\perp g}]$$

$\Rightarrow$ double helicity flip, $\cos(4\phi)$-modulation

[colorless final state]

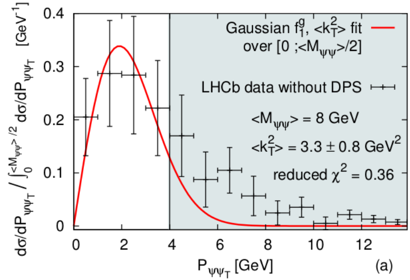


f_1^g in double J/ψ production at LHCb (I)

[From J.-P. Lansberg]

JPL, C. Pisano, F. Scarpa, M. Schlegel, PLB 784(2018)217

- f_1^g modelled as a Gaussian in $\vec{k}_T$: $f_1^g(x, \vec{k}_T^2) = \frac{g(x)}{\pi \langle k_T^2 \rangle} \exp\left(\frac{-\vec{k}_T^2}{\langle k_T^2 \rangle}\right)$
  where $g(x)$ is the usual collinear PDF
- First experimental determination [with a pure colorless final state] of $\langle k_T^2 \rangle$
  by fitting $\mathcal{C}[f_1^g f_1^g]$ over the normalised LHCb $d\sigma/dP_{\psi\psi_T}$ spectrum at 13 TeV
  from which we have subtracted the DPS yield determined by LHCb



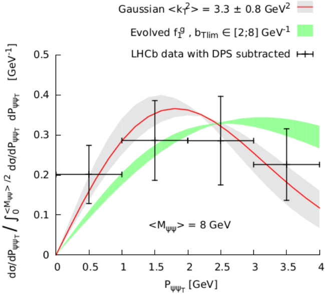
- Integration over $\phi \Rightarrow \cos(n\phi)$-terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution so far: $\langle k_T^2 \rangle \sim 3\ \text{GeV}^2$ accounts both for non-perturbative and perturbative broadenings at a scale close to $M_{\psi\psi} \sim 8$ GeV
- Disentangling such (non-)perturbative effects requires data at different scales

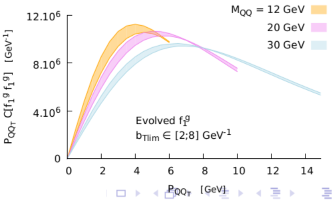
f_1^g in double J/ψ production at LHCb (II)

[From J.-P. Lansberg]

F. Scarpa, D. Boer, M.G. Echevarria, JPL, C. Pisano, M. Schlegel, EPJC (2020) 80:87

- With a fit we obtained $\langle k_T^2 \rangle \sim 3\ \mathrm{GeV}^2$
- Let us compare such a value with what a proper NLL evolution up to the scale $M_{\psi\psi} \sim 8$ GeV would give
- Evolution effects are measurable
- So far, no x dependence information





3. TMDs & quarkonia in polarized collisions

Gluon Sivers function (I)

- the Sivers function $f_{1T}^{\perp a}(x, k_{\perp a})$ describes the correlation between the parton intrinsic $k_{\perp a}$ and the transverse polarization of the proton
- non-zero Sivers effect = non-zero orbital angular momentum of parton a
- any gluon Sivers function (GSF) can be expressed in terms of two "universal" GSFs (f- and d-type):

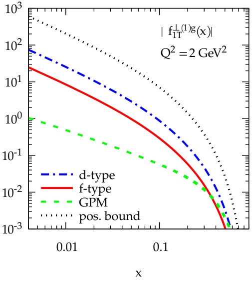
$$f_{1T}^{\perp g[U]}(x, \mathbf{k}_\perp^2) = \sum_{c=1}^{2} C_{G,c}^{[U]} f_{1T}^{\perp g(Ac)}(x, \mathbf{k}_\perp^2)$$

[Boer, Lorcé, Pisano, Zhou, Adv. High Energy Phys. (2015) 371396]

- different processes probe different GSFs
  [D'Alesio, Murgia, Pisano, Taels, PRD **96** (2017) 3, 036011]

Gluon Sivers function (II)

- first bound on the gluon Sivers function(s) in a TMD scheme and comparison with single-spin asymmetries in $p^{\uparrow}p \to J/\psi\, X$ at RHIC
  [D'Alesio, CF, Murgia, Pisano, Taels, PRD 99 (2019) 3, 036013]



$$f_{1T}^{\perp g(1)}(x) = \int d^2\mathbf{k}_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp g}(x, k_\perp^2)$$

- extension to NRQCD
  [D'Alesio, Murgia, Pisano, Rajesh, EPJ C 79 (2019) 12, 1029]
  [D'Alesio, Maxia, Murgia, Pisano, Rajesh, PRD **102** (2020) 9, 094011]

- gluon Sivers effect in J/ψ photoproduction at the future EIC
  [Rajesh, Kishore, Mukherjee, PRD **98** 1 (2018) 014007]

4. Conclusions

Conclusions

- quarkonia are very promising probes for gluon TMDs
- extensive theorethical/phenomenological effort recently (not an exhaustive list):
  - associate production of dilepton and $\Upsilon(J/\psi)$ at the LHC
    [Lansberg, Pisano, Schlegel, NPB 920 (2017) 192-210]
  - proof of TMD factorization for $pp \to \eta_{c,b} X$ at low q_T
    [Echevarria, JHEP 10 (2019) 144]
  - gluon TMDs and NRQCD matrix elements in J/ψ production at EIC
    [Bacchetta, Boer, Pisano, Taels, EPJC 80 (2020) 1, 72]
  - matching high and low q_T regions for J/ψ production in SIDIS
    [Boer, D'Alesio, Murgia, Pisano, Taels JHEP 09 (2020) 040]
  - quarkonium TMD fragmentation function in NRQCD
    [Echevarria, Makris, Scimemi, JHEP 10 (2020) 164]

Thank you
(and stay safe!)