Quarkonia in unpolarized fixed-targets

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Second LHCb Heavy Ion Workshop

Exploring Matter with Precision Charm
and Beauty Production Measurements
in Heavy Nuclei Collisions

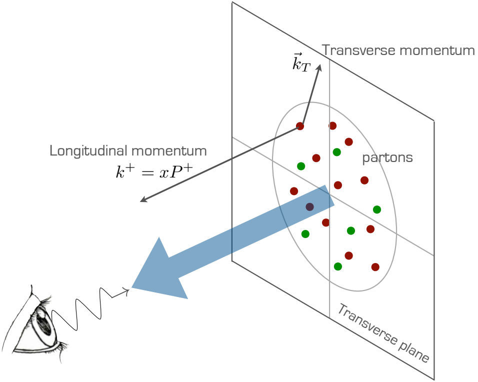
4-6 September 2019, Chia (Italy)

INFN CAGLIARI

Transverse momentum dependent parton distributions

Transverse momentum dependent distributions (TMDs)

Three-dimensional distributions: provide information on the partonic longitudinal momentum and the two-dimensional transverse momentum



There are eight TMDs for quarks and eight for gluons (more than PDFs):

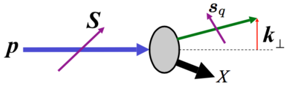
More detailed information on the structure of the proton

Quark TMDs

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_{1T}, h_{1T}^\perp$

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)

Beyond the unpolarized f_1, helicity g_{1L} and transversity h_1 surving the collinear limit, we have five more. In particular the Sivers ($f_{1T}^{\perp}$) and Boer-Mulders ($h_1^{\perp}$):



$\boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$
Sivers effect

$\boldsymbol{s}_q \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$
Boer-Mulders effect

Correlations between (proton or quark) spin and quark transverse momentum

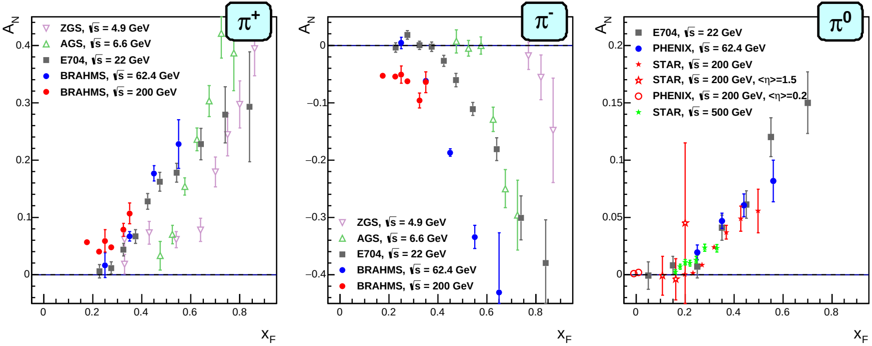
The Sivers effect is expected to give rise to transverse single spin asymmetries

Sivers (1989)

Talk by Francesco Murgia

A_N in $p^{\uparrow}p \to \pi X$ is a long standing puzzle, only a few % in twist-2 collinear QCD

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \qquad x_F = \frac{2p_L}{\sqrt{2}}$$

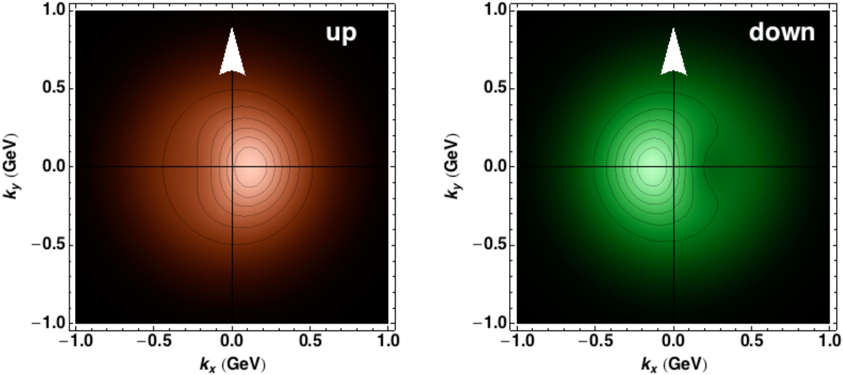


Aschenauer, D'Alesio, Murgia, EPJA52 (2016)

Almost energy independent

The Sivers function

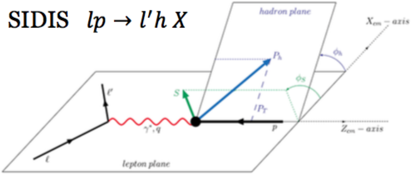
Distortion in the transverse plane

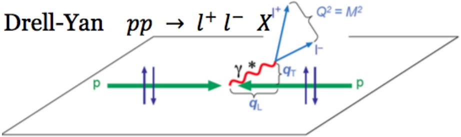


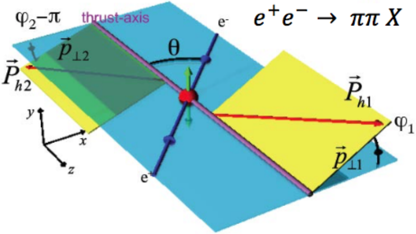
Bacchetta, Contalbrigo (2012)

Non zero Sivers effect related to parton orbital angular momentum:
Missing piece of the proton spin puzzle

Two scale processes $Q^2 \gg p_T^2$

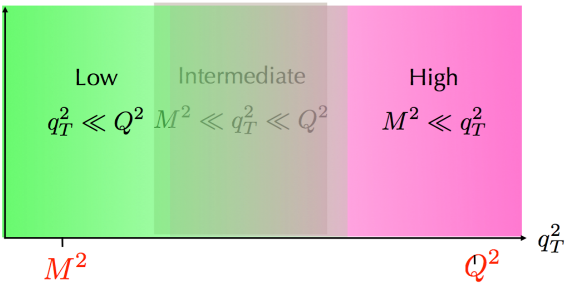


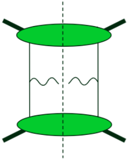




Factorization proven

Transverse q_T-spectrum of the produced hadron $\frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$: two theoretical tools

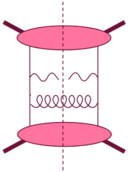




TMD

Do they describe the same dynamics or two competing mechanisms in the intermediate region?

(i.e., interpolation or sum?)



collinear PDF

GLUONS	*unpolarized*	*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}^g	$h_{1T}^g,\ h_{1T}^{\perp g}$

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

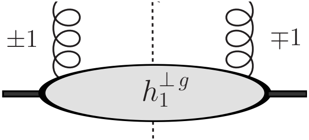
- $h_1^{\perp\, g}$: T-even distribution of linearly polarized gluons inside an unp. hadron
- h_{1T}^g, $h_{1T}^{\perp\, g}$: helicity flip distributions like h_{1T}^q, $h_{1T}^{\perp\, q}$, but T-odd, chiral even!
- $h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2}\, h_{1T}^{\perp\, g}$ does not survive under p_T integration, unlike transversity

In contrast to quark TMDs, gluon TMDs are almost unknown

The distribution of linearly polarized gluons inside an unpolarized proton: $h_1^{\perp\, g}$

Gluons inside an unpolarized hadron can be linearly polarized

It requires nonzero transverse momentum



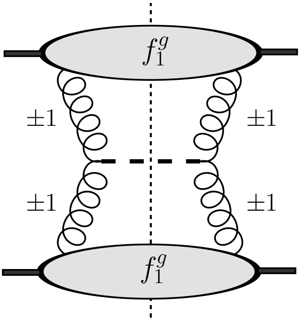
Interference between ±1 gluon helicity states

It does not need ISI/FSI to be nonzero, unlike the Sivers function. However it is affected by them $\Longrightarrow$ process dependence

Higgs boson production happens mainly via $gg \to H$

Pol. gluons affect the Higgs transverse spectrum at NNLO pQCD

Catani, Grazzini, NPB 845 (2011)



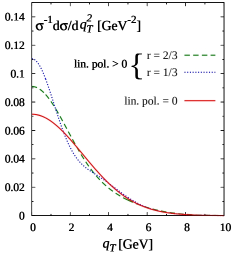
The nonperturbative distribution can be present at tree level and would contribute to Higgs production at low q_T

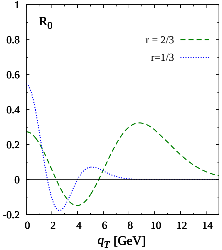
Sun, Xiao, Yuan, PRD 84 (2011)
Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012)

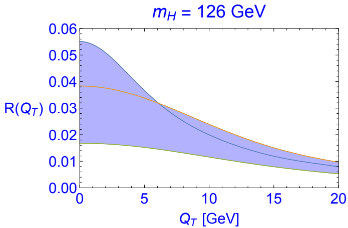
q_T-distribution of the Higgs boson

$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R(\boldsymbol{q}_T^2) \qquad R = \frac{h_1^{\perp\,g} \otimes h_1^{\perp\,g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x,\boldsymbol{p}_T^2)$$

Gaussian Model | **TMD evolution**







Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015) 158

Study of $H \to \gamma\gamma$ and interference with $gg \to \gamma\gamma$

Boer, den Dunnen, CP, Schlegel, PRL 111 (2013)

Very recent NNLO analysis

Gutierrez-Reyes, Leal-Gomez, Scimemi, Vladimirov (2019)

Quarkonium production at the LHC

$C = +1$ quarkonium production

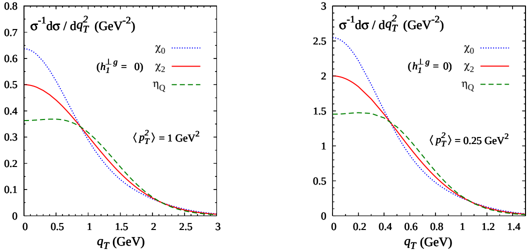
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

$$\frac{1}{\sigma(\eta_Q)}\frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \, [1 - R(\boldsymbol{q}_T^2)] \qquad \text{[pseudoscalar]}$$

$$\frac{1}{\sigma(\chi_{Q0})}\frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \, [1 + R(\boldsymbol{q}_T^2)] \qquad \text{[scalar]}$$

$$\frac{1}{\sigma(\chi_{Q2})}\frac{d\sigma(\chi_{Q2})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g$$

Boer, CP, PRD 86 (2012) 094007



Proof of factorization at NLO for $p\,p \to \eta_Q\, X$ in the Color Singlet Model (CSM)

Ma, Wang, Zhao, PRD 88 (2013), 014027; PLB 737 (2014) 103

Expected q_T modulations generated by $h_1^{\perp g}$ for $pp \to \mathcal{Q}\, X$

$\sqrt{s} = 115$ GeV

Process	expected yield	x_2 range	M [GeV]	q_T modulation
η_c	$\mathcal{O}(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c0}(1P)$	$\mathcal{O}(10^4)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c2}(1P)$	$\mathcal{O}(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$< 1\%$
$\chi_{b0}(nP)$	$\mathcal{O}(10^2)$	$0.1 \div 1$	$\mathcal{O}(10)$	$0 \div 60\%$
$\chi_{b2}(nP)$	$\mathcal{O}(10^3)$	$0.1 \div 1$	$\mathcal{O}(10)$	$< 1\%$

$$x_2 = M e^{Y_{\rm cms}} / \sqrt{s} \qquad -2.8 < Y_{\rm cms} < 0.2$$

C. Hadjidakis *et al.*, arXiv:1807.00603 [hep-ex]

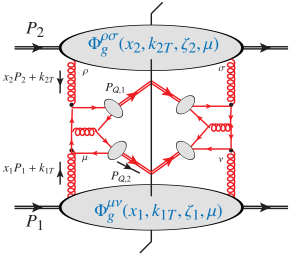
J/ψ-pair production at the LHC

J/ψ's are relatively easy to detect. Accessible at the LHC: already studied by LHCb, CMS & ATLAS

LHCb PLB 707 (2012)
CMS JHEP 1409 (2014)
ATLAS EPJC 77 (2017)

gg fusion dominant, negligible $q\bar{q}$ contributions even at AFTER@LHC energies

Lansberg, Shao, NPB 900 (2015)



No final state gluon needed for the Born contribution in the Color Singlet Model. Pure colorless final state, hence simple color structure because one has only ISI

Lansberg, Shao, PRL 111 (2013)

Negligible Color Octet contributions, in particular at low $P_T^{\Psi\Psi}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2 q_T \mathrm{d}\Omega} \approx A\, f_1^g \otimes f_1^g + B\, f_1^g \otimes h_1^{\perp g} \cos(2\phi_{CS}) + C\, h_1^{\perp g} \otimes h_1^{\perp g} \cos(4\phi_{CS})$$

Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)

- valid up to corrections $\mathcal{O}(q_T/Q)$
- Y: rapidity of the J/ψ-pair, along the beam in the hadronic c.m. frame
- $\mathrm{d}\Omega = \mathrm{d}\cos\theta_{CS}\, \mathrm{d}\phi_{CS}$: solid angle for J/ψ-pair in the Collins-Soper frame

Analysis similar to the one for $pp \to \gamma\gamma X$, $pp \to J\psi\, \gamma^{(*)} X$, $pp \to H\,\mathrm{jet}\,X$

Qiu, Schlegel, Vogelsang, PRL 107 (2011)
den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014)
Lansberg, CP, Schlegel, NPB 920 (2017)
Boer, CP, PRD 91 (2015)

The three contributions can be disentangled by defining the transverse moments

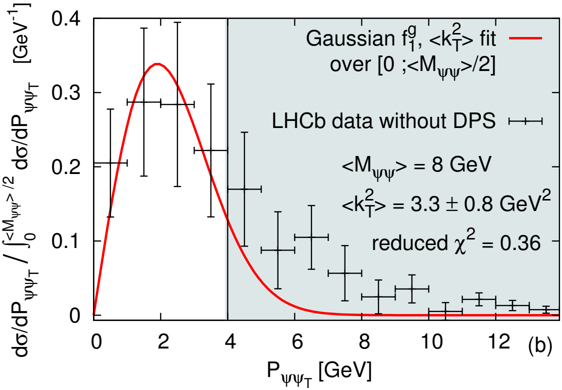
$$\langle \cos n\phi_{CS} \rangle \equiv \frac{\int_0^{2\pi} \mathrm{d}\phi_{CS}\, \cos(n\,\phi_{CS})\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2 q_T \mathrm{d}\Omega}}{\int_0^{2\pi} \mathrm{d}\phi_{CS}\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2 q_T \mathrm{d}\Omega}} \qquad (n = 2, 4)$$

$$\int \mathrm{d}\phi_{CS}\, \mathrm{d}\sigma \implies f_1^g \otimes f_1^g$$

$$\langle \cos 2\phi_{CS} \rangle \implies f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi_{CS} \rangle \implies h_1^{\perp g} \otimes h_1^{\perp g}$$

We consider $q_T = P_T^{\Psi\Psi} \leq M_{\Psi\Psi}/2$ in order to have two different scales



Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
LHCb Coll., JHEP 06 (2017)

Gaussian model: $$f_1^g(x, \boldsymbol{k}_T^2) = \frac{f_1^g(x)}{\pi \langle k_T^2 \rangle} \exp\left(-\frac{\boldsymbol{k}_T^2}{\langle k_T^2 \rangle} \right)$$

Expected modulations generated by $h_1^{\perp g}$ for $pp \to J/\psi\,\gamma\,X$, $pp \to J/\psi\,J/\psi\,X$

$\sqrt{s} = 115$ GeV

Process	expected yield	x_2 range	M [GeV]	$\cos 2\phi$ mod.	$\cos 4\phi$ mod.
$J/\psi + \gamma$	$1000 \div 2000$	$0.1 \div 0.6$	$\mathcal{O}(10)$	$0 \div 5\%$	$0 \div 2\%$
$J/\psi + J/\psi$	$300 \div 1500$	$0.1 \div 0.8$	$8 \div 12$	$0 \div 8\%$	$0 \div 20\%$

$$x_2 = M e^{Y_{\rm cms}}/\sqrt{s} \qquad -2.8 < Y_{\rm cms} < 0.2$$

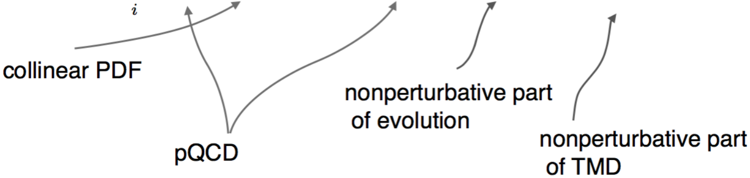
C. Hadjidakis *et al.*, arXiv:1807.00603 [hep-ex]

TMD evolution

TMD evolution
Fourier transform

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-i b_\perp \cdot k_\perp} \widetilde{f}_1^a(x, b_\perp; \mu^2)$$

$$\widetilde{f}_1^a(x, b_T; \mu^2) = \sum_i (\tilde{C}_{a/i} \otimes f_1^i)(x, b_*; \mu_b) e^{\tilde{S}(b_*; \mu_b, \mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\mathrm{NP}}^a(x, b_T)$$



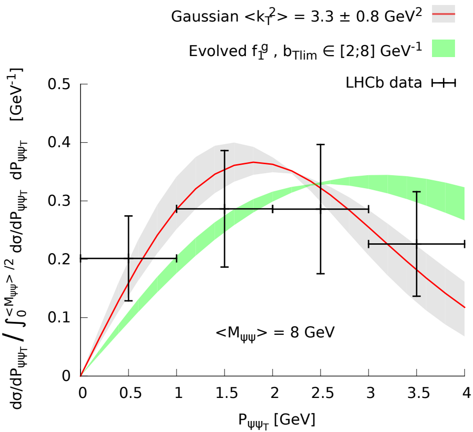
Rogers, Aybat, PRD 83 (11)
Collins, *Foundations of Perturbative QCD* (11)

Different schemes have been suggested

Collins, Soper, Sterman, NPB 250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

Assumption for nonperturbative evolution: $g_K = -g_2 \frac{b_T^2}{4}$

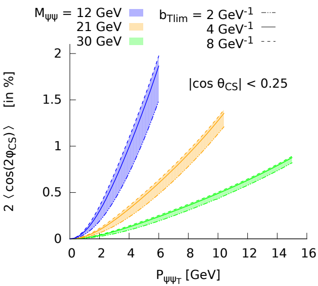
Normalized $P_T^{\Psi\Psi}$-spectrum for J/ψ-pair production

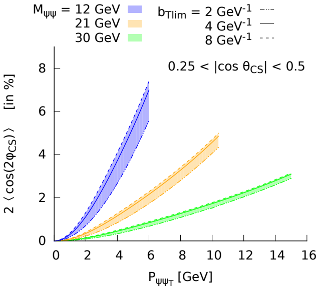


Scarpa, Böer, Lansberg, Echevarria, CP, Schlegel, in preparation

$b_{\rm Tlim}$ is the value at which the nonpertubative Sudakov factor $e^{-S_{\rm NP}(b_T^2)} \sim 10^{-3}$

Asymmetries decrease as the hard scale increases





Scarpa, Böer, Lansberg, Echevarria, CP, Schlegel, in preparation

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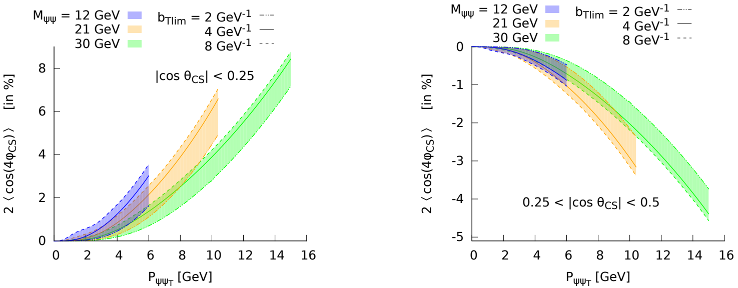

Scarpa, Böer, Lansberg, Echevarria, CP, Schlegel, in preparation

Conclusions

- Spin effects are accessible without polarization measurements
- Quarkonia are good probes for gluon TMDs: first extraction of unpolarized gluon TMD from LHCb data on di-J/Ψ production
- Azimuthal asymmetries produced by polarized gluon TMDs in quarkonium production at the LHC can be sizeable in specific kinematic regions
- Fixed target experiment would constrain gluon TMDs in a complementary kinematic region w.r.t. the collider mode: larger x and smaller Q^2
- This is important to test QCD evolution and determine the relevance of nonperturbative contributions, in analogy to quark TMDs