The TMD Structure of Hadrons: Status and Prospects

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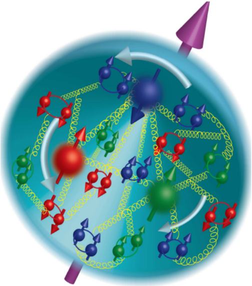
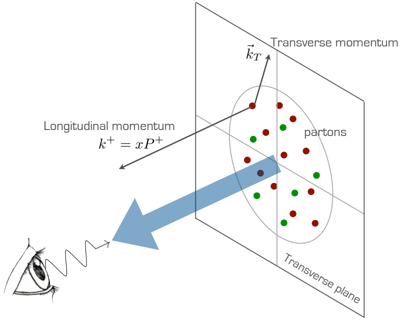
University and INFN Cagliari



IWHSS 2023
26 - 28 June 2023
Prague (Czech Republic)

TMD factorization and process dependence

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

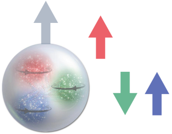


Renormalization scale μ and the Collins-Soper scale ζ not shown explicitly

More detailed information on the proton's structure as compared to PDFs: 1D description is not always satisfactory, see i.e. spin effects

Proton spin puzzle

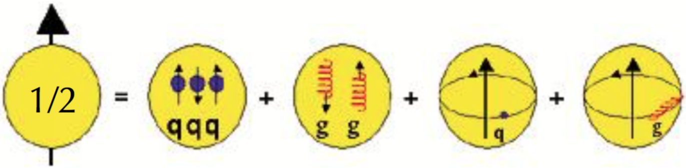
The proton has spin 1/2, the three *valence* quarks have also spin 1/2, we expect:



However: only 30% of the spin of the proton comes from the spin of the quarks

First measurement by the European Muon Collaboration (EMC, CERN 1987)

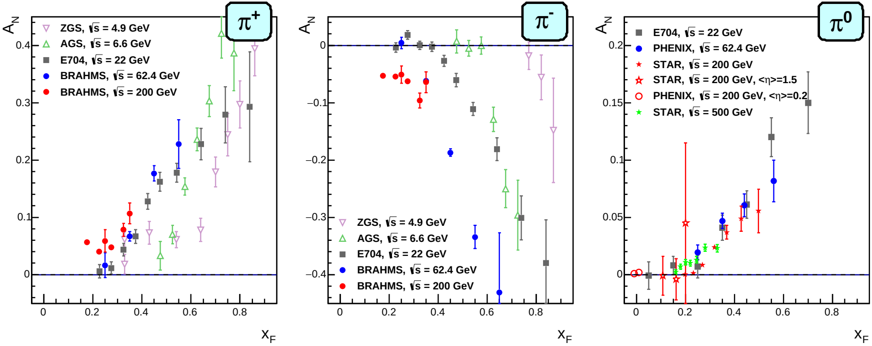
$$\vec{\mu}\vec{p} \to \mu X \qquad\qquad A = \frac{(\vec{\mu}\vec{p}) - (\vec{\mu}\,\overleftarrow{p})}{(\vec{\mu}\,\vec{p}) + (\vec{\mu}\,\overleftarrow{p})}$$



The partonic orbital angular momentum needs to be considered

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

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

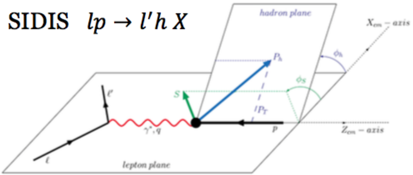


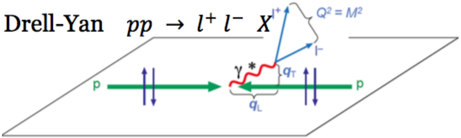
Aschenauer, D'Alesio, Murgia, EPJA52 (2016)

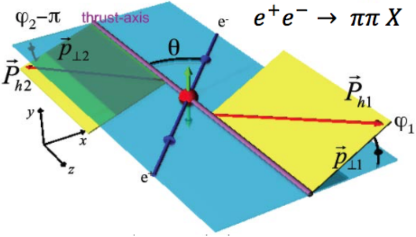
Almost energy independent

TMD factorization does not hold, collinear twist-3 approach more popular

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







Factorization proven

All orders in α_s

Leading order in powers of $1/Q$ (twist)

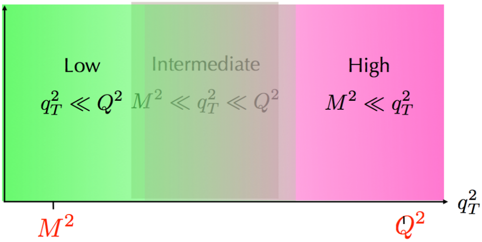
Collins, Cambridge University Press (2011)
Boussarie et al, TMD handbook 2304.03302

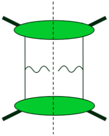
Attempts to establish factorization at one-loop and next-to-leading power

Rodini, Vladimirov, 2306.09495
Gamberg, Kang, Shao, Terry, Zhao, 2211.13209

Three physical scales, two theoretical tools

Bacchetta, Boer, Diehl, Mulders, JHEP 08 (2008)

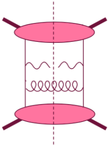




TMD

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

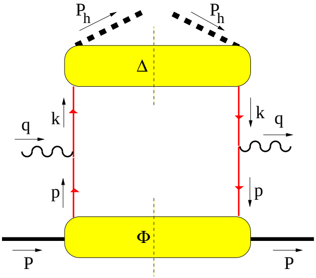
(i.e., **interpolation** or **sum?**)



collinear PDF

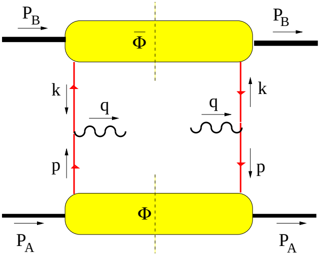
Hard partonic interactions can be separated from nonperturbative correlators

SIDIS



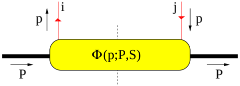
$\gamma^* p \to h X$

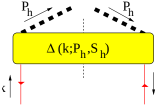
Drell-Yan



$p\, p \to \gamma^* X$

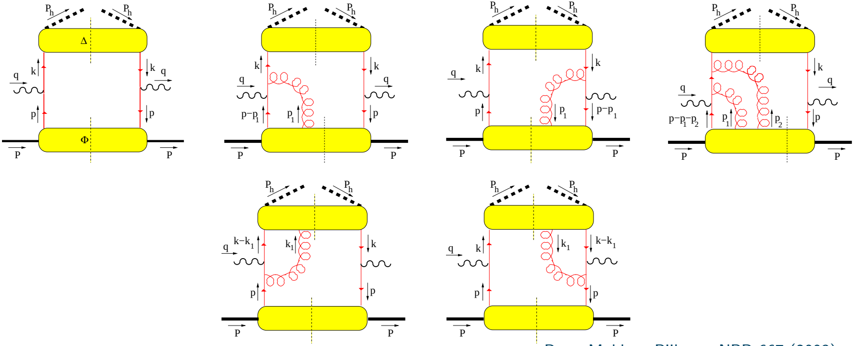
Parton correlators Φ and Δ describe the soft hadron ↔ parton transitions





Parametrized in terms of distribution and fragmentation functions

Resummation of all gluon exchanges leads to *gauge links* in the correlators Φ, Δ



Boer, Mulders, Pijlman, NPB 667 (2003)

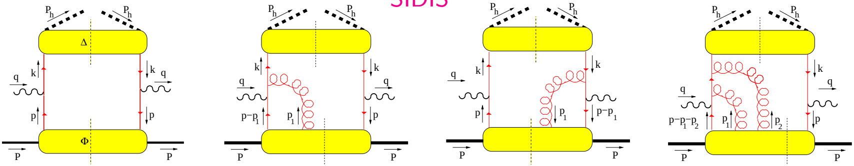
$$\mathcal{U}^{\mathcal{C}}_{[0,\xi]} = \mathcal{P}\exp\left(-ig\int_{\mathcal{C}[0,\xi]} \mathrm{d}s_\mu A^\mu(s)\right)$$

The path $\mathcal{C}$ depends on the color interactions, *i.e.* on the specific process

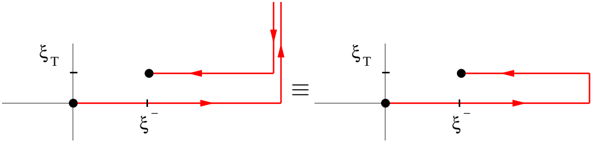
Gauge invariant definition of Φ (not unique)

$$\Phi^{[\mathcal{U}]} \propto \left\langle P, S \left| \overline{\psi}(0)\, \mathcal{U}^{\mathcal{C}}_{[0,\xi]}\, \psi(\xi) \right| P, S \right\rangle$$

SIDIS



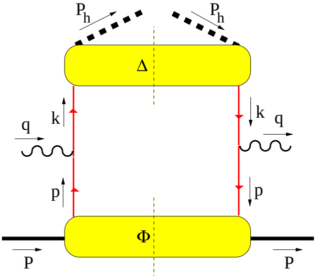
Belitsky, Ji, Yuan, NPB 656 (2003)
Boer, Mulders, Pijlman, NPB 667 (2003)



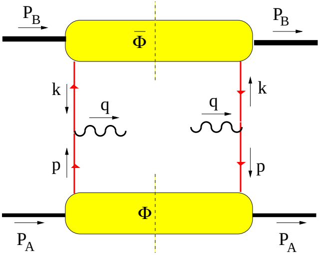
$\mathcal{U}^{[+]}_{[0,\xi]}$

Possible effects in transverse momentum observables (ξ_T is conjugate to k_T)

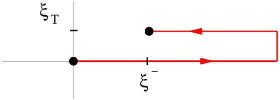
SIDIS

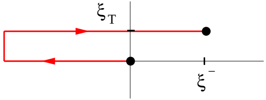


Drell-Yan



$\mathcal{U}^{[+]}_{[0,\xi]}$

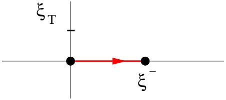




$\mathcal{U}^{[-]}_{[0,\xi]}$

Belitsky, Ji, Yuan, NPB 656 (2003)
Boer, Mulders, Pijlman, NPB 667 (2003)

$\int \mathrm{d}k_T \longrightarrow \xi_T = 0 \longrightarrow$



the same in both cases

Quark TMDs

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)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

Global extractions of the unpolarized TMD f_1 up to N^{3}LL (evolution)

Pavia 2017, JHEP 06 (2017)
Scimemi, Vladimirov, JHEP 06 (2020)
MAP Collaboration, JHEP (2022)

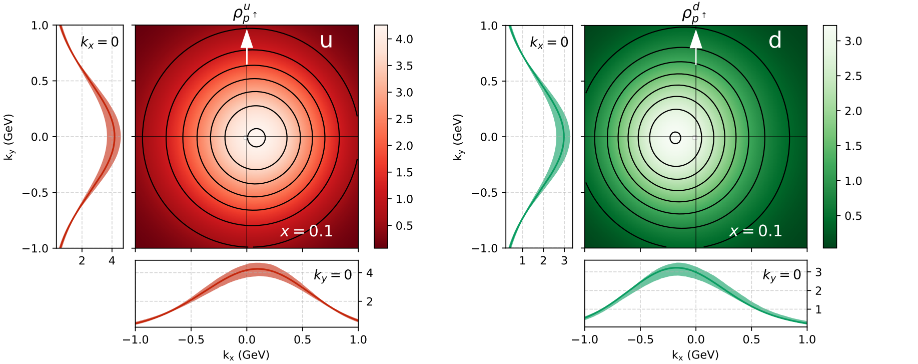
Global extractions of the Sivers function $f_{1T}^\perp$ up to N^{3}LL

Bury, Prokudin, Vladimirov, PRL 126 (2021)
Echevarria, Kang, Terry, JHEP 01 (2021)
Bacchetta, Delcarro, Pisano, Radici, CP, PLB 827 (2022)

See talks by M. Radici and A. Vladimirov

Distortion in the transverse plane of the TMD quark distribution in a $p^\uparrow$

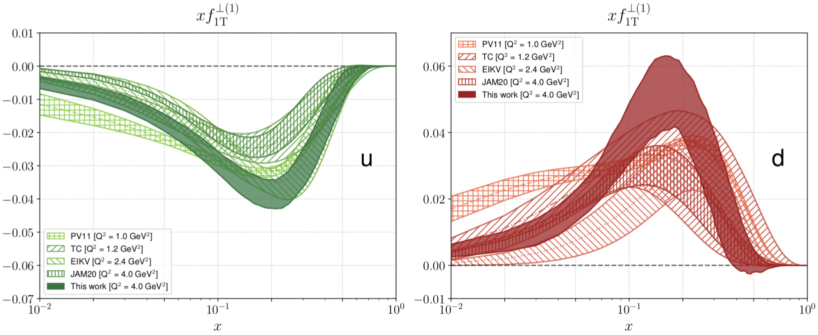
$$\Phi_{q/p^\uparrow}^{[\gamma^+]}(x, k_x, k_y) = f_1^q(x, k_T^2) - \frac{k_x}{M} f_{1T}^{\perp q}(x, k_T^2) \qquad [Q^2 = 4 \text{ GeV}^2]$$



Bacchetta, Delcarro, Pisano, Radici, CP, PLB 827 (2022)

Non zero Sivers effect related to parton orbital angular momentum

$$f_{1T}^{\perp(1)\,q}(x) = \int \mathrm{d}^2\boldsymbol{k}_T \, \frac{k_T^2}{2M_p^2} \, f_{1T}^{\perp\,q}(x, \boldsymbol{k}_T^2)$$



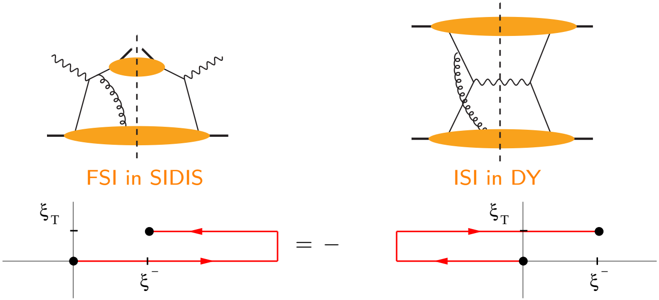
Bacchetta, Delcarro, Pisano, Radici, CP, PLB 827 (2022)

More data from CERN, JLab, EIC will help to reduce error bands and extend the ranges in x and Q^2

Fundamental test of the theory: valid for all T-odd TMDs

$$f_{1T}^{\perp\,[DY]}(x,\boldsymbol{k}_\perp^2) = -f_{1T}^{\perp\,[SIDIS]}(x,\boldsymbol{k}_\perp^2)$$

Collins, PLB 536 (2002)

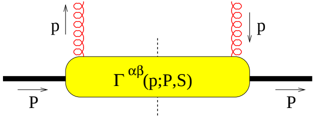


Still under experimental scrutiny

ISI/FSI lead to process dependence of TMDs, could even break factorization

Collins, Qiu, PRD 75 (2007)
Collins, PRD 77 (2007)
Rogers, Mulders, PRD 81 (2010)

Gluon TMDs



Gauge invariant definition of $\Gamma^{\mu\nu}$

$$\Gamma^{[\mathcal{U},\mathcal{U}']\mu\nu} \propto \langle P,S|\,\mathrm{Tr}_c\big[\,F^{+\nu}(0)\,\mathcal{U}^{\mathcal{C}}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}^{\mathcal{C}'}_{[\xi,0]}\,\big]\,|P,S\rangle$$

Mulders, Rodrigues, PRD 63 (2001)
Buffing, Mukherjee, Mulders, PRD 88 (2013)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

The gluon correlator depends on two path-dependent gauge links

$ep \to e' Q\overline{Q} X$, $ep \to e'\,\mathrm{jet\,jet}\,X$ probe gluon TMDs with $[++]$ gauge links

$pp \to \gamma\gamma X$ (and/or other CS final state) probes gluon TMDs with $[--]$ gauge links

$pp \to \gamma\,\mathrm{jet}\,X$ probes an entirely independent gluon TMD: $[+-]$ links (dipole)

Gluon TMDs

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 gluon Sivers functions
Sign change test

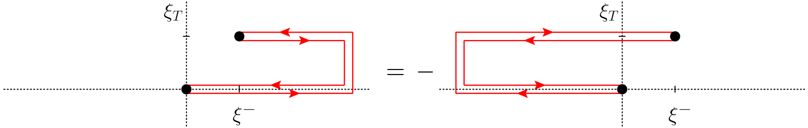
Related Processes

$ep^{\uparrow} \to e' Q\overline{Q}X$, $ep^{\uparrow} \to e'\ \mathrm{jet}\,\mathrm{jet}\,X$ probe GSF with $[++]$ gauge links (WW)

$p^{\uparrow}p \to \gamma\gamma X$ (and/or other CS final state) probe GSF with $[--]$ gauge links

Analogue of the sign change of $f_{1T}^{\perp\,q}$ between SIDIS and DY (true also for h_1^g and $h_{1T}^{\perp\,g}$)

$$f_{1T}^{\perp\,g\,[e\,p^{\uparrow}\to e'\,Q\overline{Q}\,X]} = -f_{1T}^{\perp\,g\,[p^{\uparrow}\,p\to\gamma\,\gamma\,X]}$$

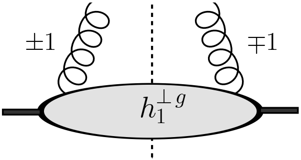


Boer, Mulders, CP, Zhou (2016)

Motivation to study gluon Sivers effects at both RHIC and the EIC

Gluons inside an unpolarized hadron can be linearly polarized

It requires nonzero transverse momentum



Interference between ± 1 gluon helicity states

Like the unpolarized gluon TMD, it is T-even and exists in different versions:

- $[++] = [--]$ (WW) (SIDIS and DY-like process)

Gluons can be probed in heavy quark production in both *ep* and *pp* scattering

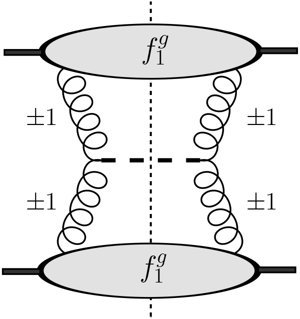
Mukherjee, Rajesh, EPJC 77 (2017)
Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
Rajesh, Kishore, Mukherjee, PRD 98 (2018)
Bacchetta, Boer, CP, Taels, EPJC 80 (2020)

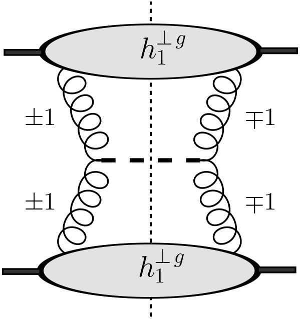
See talk by A. Mukherjee

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

Pol. gluons affect the Higgs transverse spectrum at NNLO pQCD

Catani, Grazzini, NPB 845 (2011)





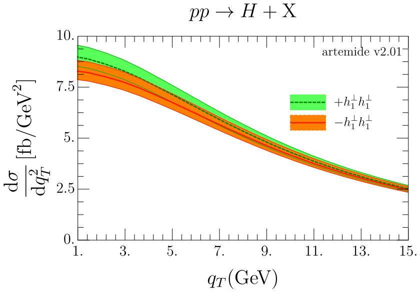
The nonperturbative distribution can be present at tree level and would contribute to Higgs production at low q_T

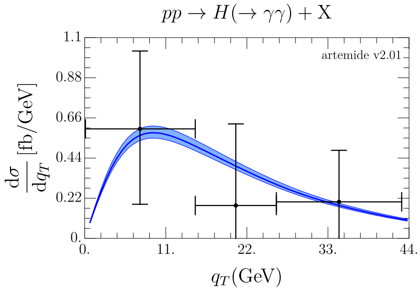
Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012)
Boer, den Dunnen, CP, Schlegel, PRL 111 (2013)
Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015)

q_T-distribution of the Higgs boson

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

The perturbative tails of f_1^g and $h_1^{\perp\,g}$ (matching coefficients to collinear PDFs) are known up to $\mathcal{O}(\alpha_s^2)$ (NNLO); g_{1L} up to $\mathcal{O}(\alpha_s)$ (NLO)





Gutierrez-Reyes, Leal-Gomez, Scimemi, Vladimirov, JHEP 11 (2019) 121

The matching of the other gluon TMDs is still unkown

$C = +1$ quarkonium production

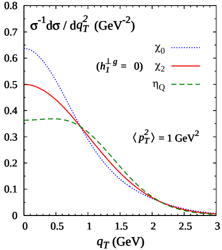
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

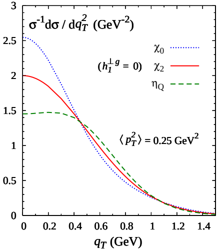
$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \, [1 - R(\boldsymbol{q}_T^2)] \qquad \text{[pseudoscalar]} \qquad R(\boldsymbol{q}_T^2) = \frac{h_1^{\perp\, g} \otimes h_1^{\perp\, g}}{f_1^g \otimes f_1^g}$$

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

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

Boer, CP, PRD 86 (2012)



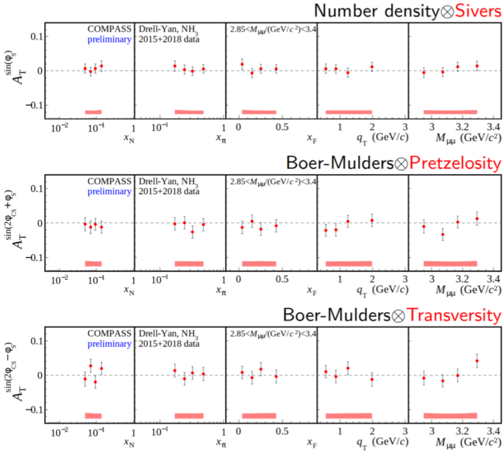


Proof of factorization at NLO for $p\,p \to \eta_Q\, X$ in the Color Singlet Model (CSM)

Ma, Wang, Zhao, PRD 88 (2013); PLB 737 (2014)
Echevarria, JHEP 1910 (2019)

Future fixed target experiments at LHC

Single spin asymmetries compatible with zero: cancellation effects?



M. Chiosso, talk at SarWorS (2023)

Models for the gluon TMDs of the pion and shape functions are needed

For example, spectator model already used for the proton

Bacchetta, Celiberto, Radici, Taels, EPJC 80 (2020)
Chakrabarti *et al. (2023)*

Conclusions

- Unpolarized quark TMDs of the proton are quite well-known, theoretical analysis can be improved by looking at Y-term, flavor dependence, ...
- First attempts to extract quark TMDs of the pion, while the gluon ones are unkown; gluon TMDs of the proton are also poorly known
- Gluon TMDs can be probed in open heavy quark pair and quarkonium production in both ep and pp collisions
- If TMD factorization is applicable to quarkonium production, shape functions will have to be included in the expressions for the observables

  Boer, Maxia, CP, Yuan, 2304.09473
- COMPASS/AMBER, JLab, LHCspin and EIC data will shed light on TMDs, shape functions and on the mechanisms underlying quarkonium production