Three-Dimensional Imaging of the Nucleon

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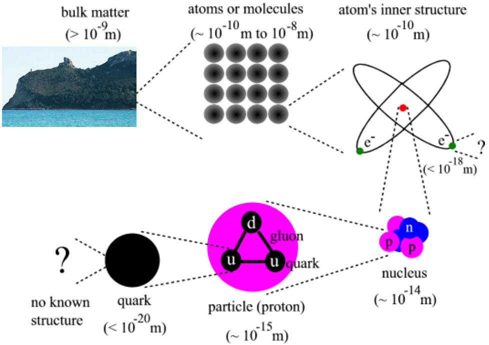
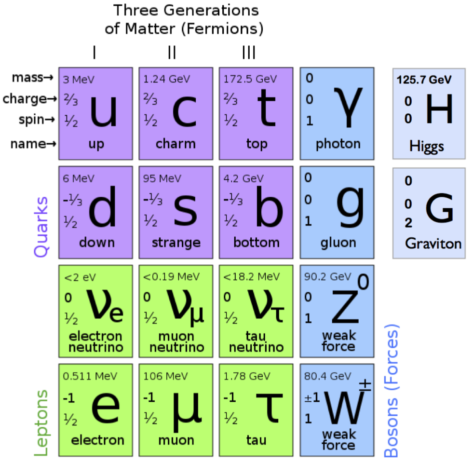
INFN CAGLIARI

Nucleons (protons, neutrons) responsible for $> 95\%$ of the mass of matter



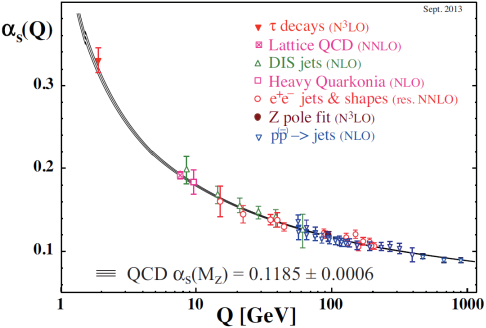
Nucleons are not pointlike, they are made of quarks and gluons (partons)

QCD is the theory of strong interactions among partons, like QED for electrons



Unlike photons, gluons carry (color) charge

Running coupling: the strong coupling α_s changes with the characteristic energy

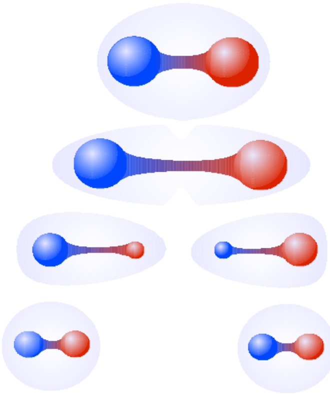


Asymptotic freedom: at small distance the quarks and gluons are (almost) free particles: perturbative approach is applicable

Discovered by Gross, Wilczek and Politzer (Nobel Prize 2004)

Quarks and gluons have never been observed as free particles

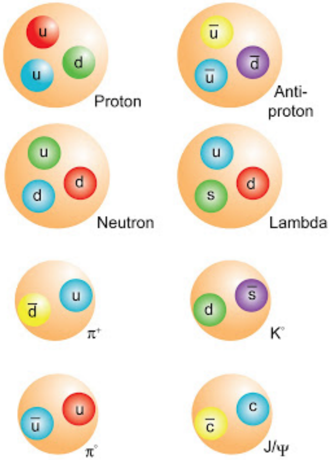
Quark-antiquark pairs always recombine to form a colorless states



Mathematical proof: among the seven Millennium Prize Problems (2000)

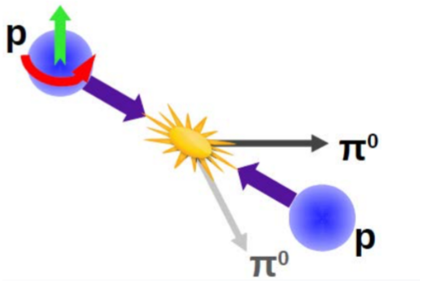
The neutral composites observed in nature are the hadrons:

- baryons made of three *valence* quarks
- mesons made of a *valence* quark-antiquark pair



How do we probe the structure of the nucleon?

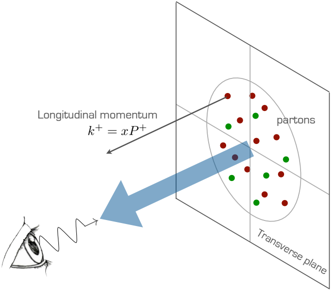
Scattering processes at high energy scales $Q \gg M_p$ (proton mass) provide important information on the internal structure of hadrons

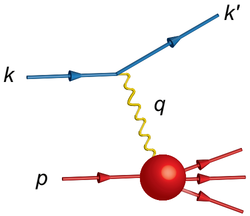


Partons are usually taken to be collinear to their parent hadrons

The probe defines a longitudinal direction

1D-Parton Distribution Functions are universal

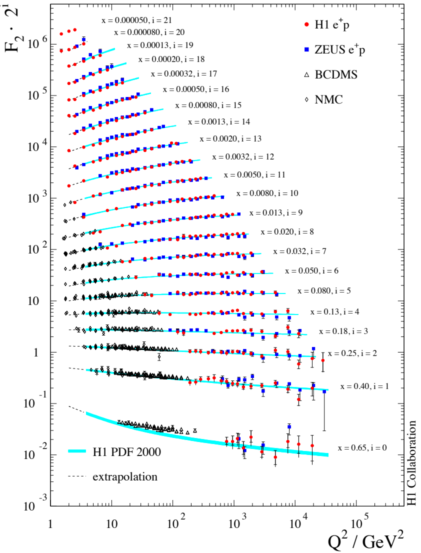




x: fraction of proton's momentum carried by the struck quark

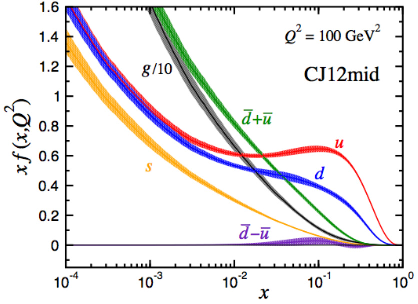
$Q^2 \equiv -q^2$: defines the resolution of the measurement

Structure Function F_2



$$F_2(x, Q^2) = x \sum_q e_q^2\, f_1^q(x, Q^2)$$

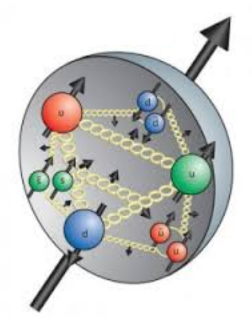
1D collinear parton distributions



CTEQ-JLAB Collaboration, PRD 87 (2013)

Scaling violations: great success of QCD evolution!

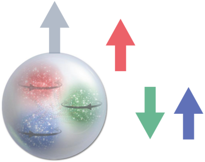
The one-dimensional picture of the proton is not always satisfactory:
a more complete description is nedeed



Spin: fundamental quantum degree of freedom, a tool to study the inner structure of a composite system like the nucleon

The proton spin crisis

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

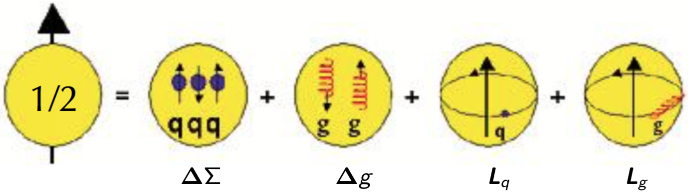
First measurement by the European Muon Collaboration (EMC, CERN 1987)

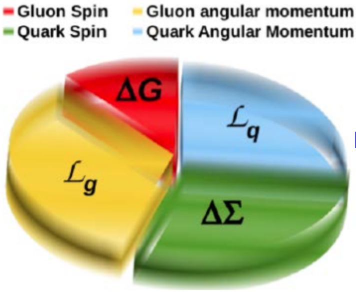
$$\vec{\mu}\vec{p} \to \mu X \qquad\qquad A = \frac{(\vec{\mu}\vec{p}) - (\vec{\mu}\,\overleftarrow{p})}{(\vec{\mu}\,\vec{p}) + (\vec{\mu}\,\overleftarrow{p})}$$

Spin asymmetry in longitudinally polarized muon-proton scattering

Proton spin puzzle

One needs to take into account the partonic orbital angular momentum



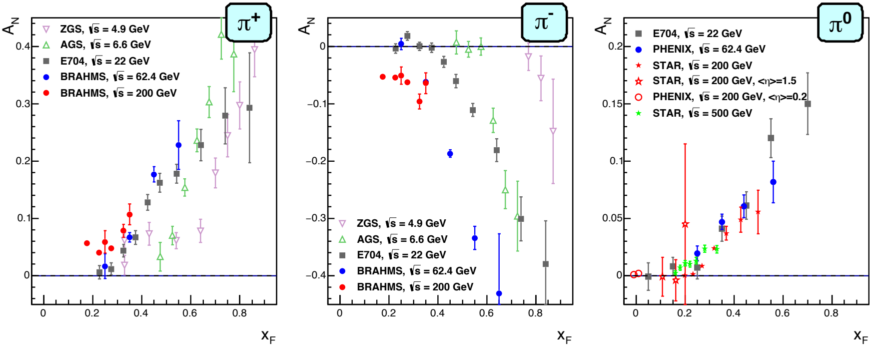


Different definitions of orbital angular momentum:
the decomposition is highly non trivial

Leader, Lorcé, Phys Rept 541 (2014)

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

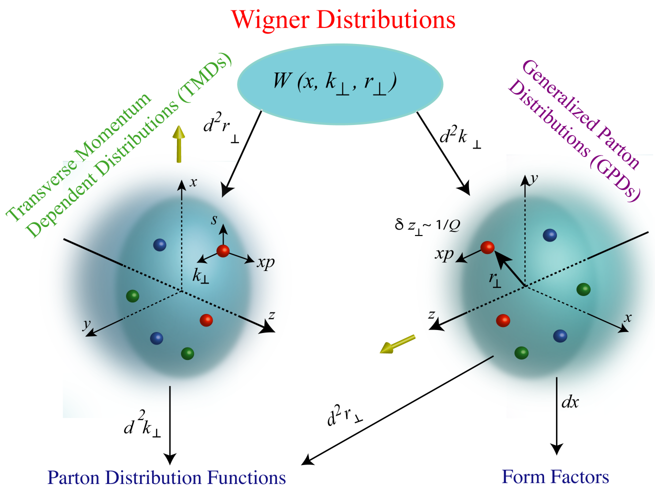
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \qquad x_F = \frac{2p_L}{\sqrt{2}}$$



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

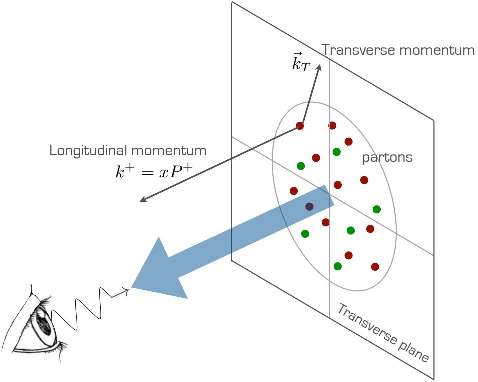
Almost energy independent

Proton's image in 3D: in momentum (TMDs) and in configuration space (GPDs)



Transverse momentum dependent parton distributions

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



The are eight TMDs for quarks (many more than collinear PDFs!):

More detailed information on the structure of the proton

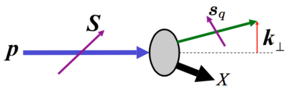
Quark TMDs

Leading Twist TMDs

Nucleon Spin   Quark Spin

		Quark Polarization		
		Un-Polarized (U)	**Longitudinally Polarized (L)**	**Transversely Polarized (T)**
Nucleon Polarization	**U**	f_1 =		$h_1^{\perp}$ = — Boer-Mulders
	L		g_{1L} = — Helicity	$h_{1L}^{\perp}$ = —
	T	$f_{1T}^{\perp}$ = — Sivers	$g_{1T}^{\perp}$ = —	h_1 = — Transversity $h_{1T}^{\perp}$ = —

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

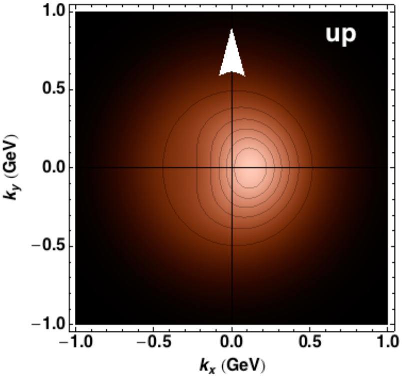
$\boldsymbol{s}_q \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$
Boer-Mulders effect

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)

Distorsion in the transverse plane



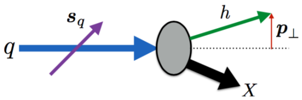
Bacchetta, Contalbrigo (2012)

Non zero Sivers effect related to parton orbital angular momentum

Two independent TMD fragmentation functions for unpolarized hadrons:

- The unpolarized fragmentation function D_1
- The Collins function $H_1^\perp$, which describes the correlation between the spin of the fragmenting quark and the hadron transverse momentum

Collins, 1992



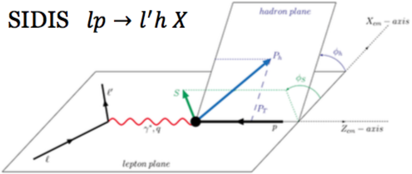
Collins effect $\propto \; \boldsymbol{s}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_\perp)$

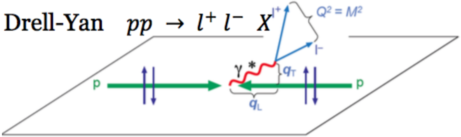
Collins effect is one of the mechanisms underlying transverse spin asymmetries

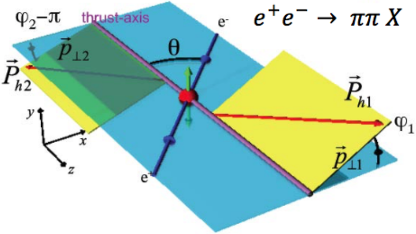
TMD fragmentation functions expected to be universal (unlike distributions)

TMD factorization

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







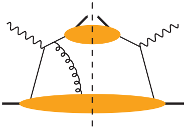
Factorization proven

TMD distributions are affected by initial (ISI) and final (FSI) state interactions

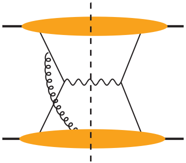
Encoded in the *Wilson lines*, needed to have a gauge invariant definition of TMDs

Fundamental test of TMD theory

$$f_{1T}^{\perp\,[DY]}(x, \boldsymbol{k}_\perp^2) = -f_{1T}^{\perp\,[SIDIS]}(x, \boldsymbol{k}_\perp^2) \qquad h_1^{\perp\,[DY]}(x, \boldsymbol{k}_\perp^2) = -h_1^{\perp\,[SIDIS]}(x, \boldsymbol{k}_\perp^2)$$



FSI in SIDIS

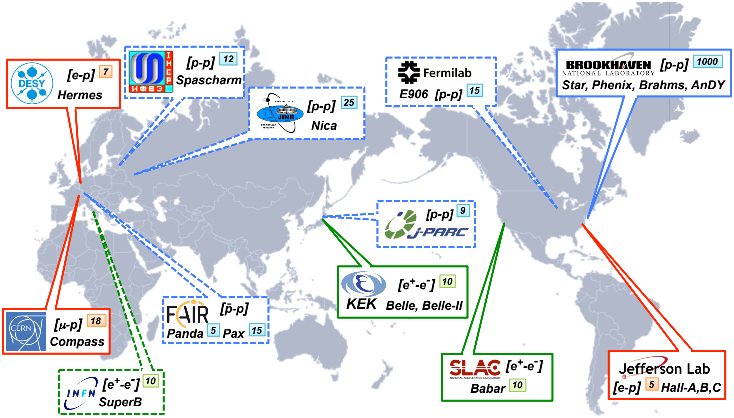


ISI in DY

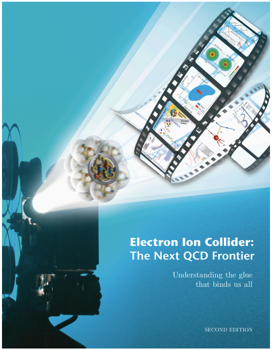
ISI/FSI lead to process dependence of TMDs, could even break factorization

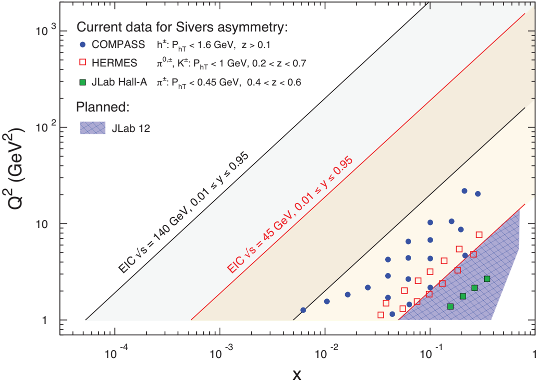
Rogers, Mulders, PRD81 (2010)

TMDs are, or will be, under experimental investigation all over the world



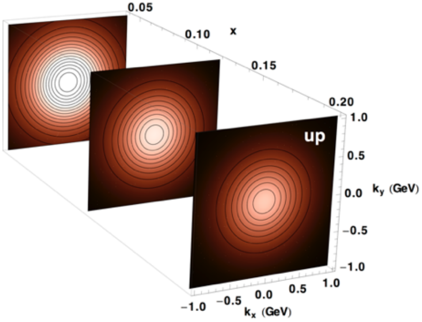
Bacchetta, Contalbrigo (2012)





- Access to small-x domain
- Space, momentum and spin distributions of gluon and sea quarks
- Missing and complementary information on TMDs and GPDs

Extraction of unpolarized quark distributions

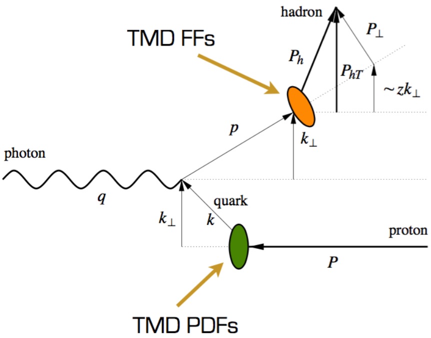


- Are unpolarized quark TMDs universal?
- Does TMD evolution allow for a description of the data at different Q^2?
- How wide is the transverse momentum distribution? Is it wider at low x?

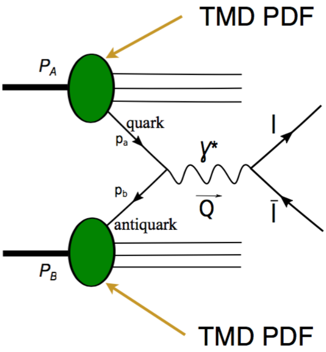
Bacchetta, Delcarro, CP, Radici (Pavia 2016)
JHEP 1706 (2017) 081

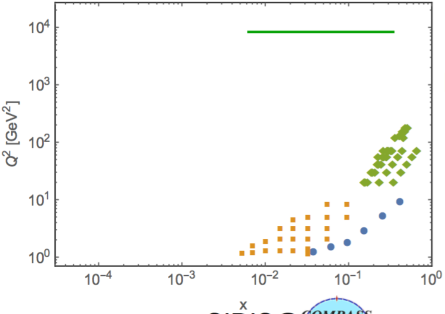
Semi-inclusive DIS vs DY

$$l(\ell) + N(\mathcal{P}) \to l(\ell') + h(\mathcal{P}_h) + X$$



$$A + B \to \gamma^* \to l^+ l^-$$
$$A + B \to Z \to l^+ l^-$$





Z production@ Fermilab

Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803

Drell-Yan@ Fermilab

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

SIDIS@ hermes

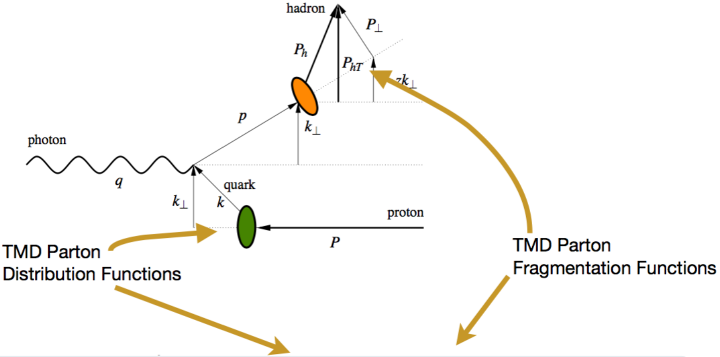
Airapetian et al., PRD87 (2013)

SIDIS@ COMPASS

Adolph et al., EPJ C73 (13)

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	NLL/ NLO	✘	✘	✔	✔	98
Pavia 2013 arXiv:1309.3507	No evo	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	No evo	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NNLL/ NLO	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	NLL/ LO	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2016 arXiv:1703.10157	NLL/ LO	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL/ NNLO	✘	✘	✔	✔	309

SIDIS structure function



$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2) \int d^2\boldsymbol{k}_T\, d^2\boldsymbol{P}_T\, f_1^a(x,\boldsymbol{k}_T^2;\mu^2)\, D_1^{h/a}(z,\boldsymbol{P}_T^2;\mu^2)\, \delta^2(z\boldsymbol{k}_T - \boldsymbol{P}_{hT} + \boldsymbol{P}_T)$$
$$+ Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

$\mathcal{H}^a_{UU,T} \approx \mathcal{O}(\alpha_S^0)$, $Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) \approx 0$ in Pavia 2016

Multiplicities: $m_N^h(x,z,\boldsymbol{P}_{hT}^2,Q^2) = \dfrac{d\sigma_N^h/dx\,dz\,d\boldsymbol{P}_{hT}^2\,dQ^2}{d\sigma_{\mathrm{DIS}}/dx\,dQ^2} \approx \dfrac{2\pi|\boldsymbol{P}_{hT}|F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)}{F_T(x,Q^2)}$

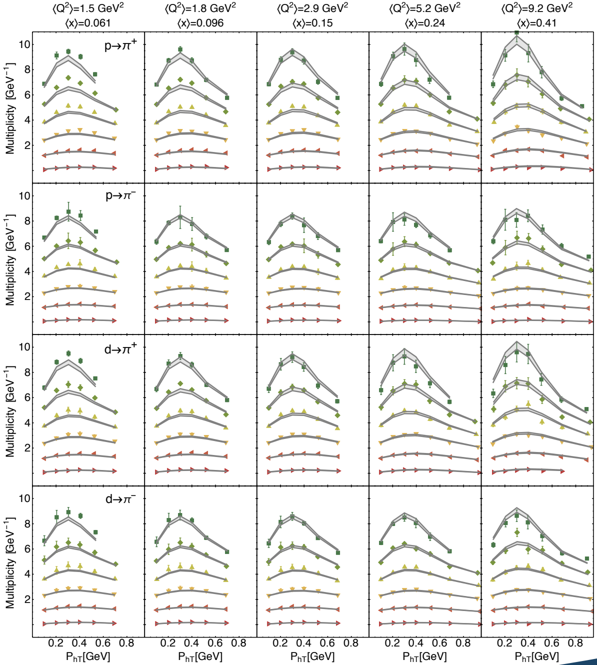
Total number of data points: 8059

Total number of free parameters: 11

- 4 for TMD PDFs
- 6 for TMD FFs
- 1 for TMD evolution

Total $\chi^2/\text{dof} = 1.55 \pm 0.05$

HERMES data
Pion production



- ⟨z⟩=0.24 (offset=5)
- ⟨z⟩=0.28 (offset=4)
- ⟨z⟩=0.34 (offset=3)
- ⟨z⟩=0.43 (offset=2)
- ⟨z⟩=0.54 (offset=1)
- ⟨z⟩=0.70 (offset=0)

χ^2/dof

4.83

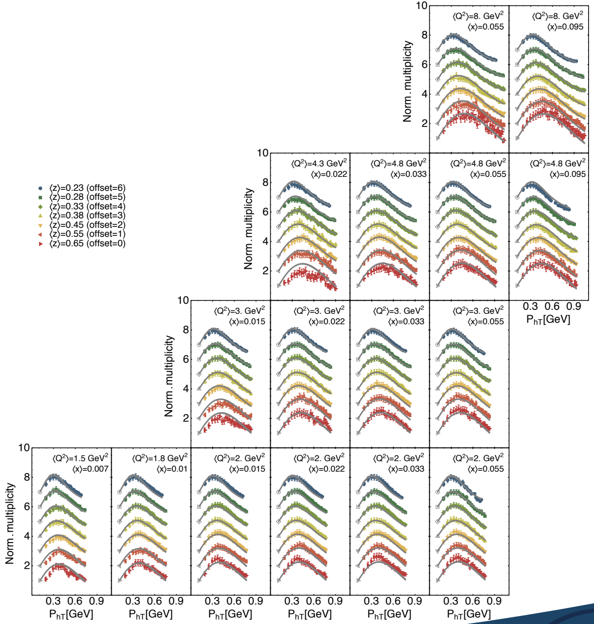
2.47

3.46

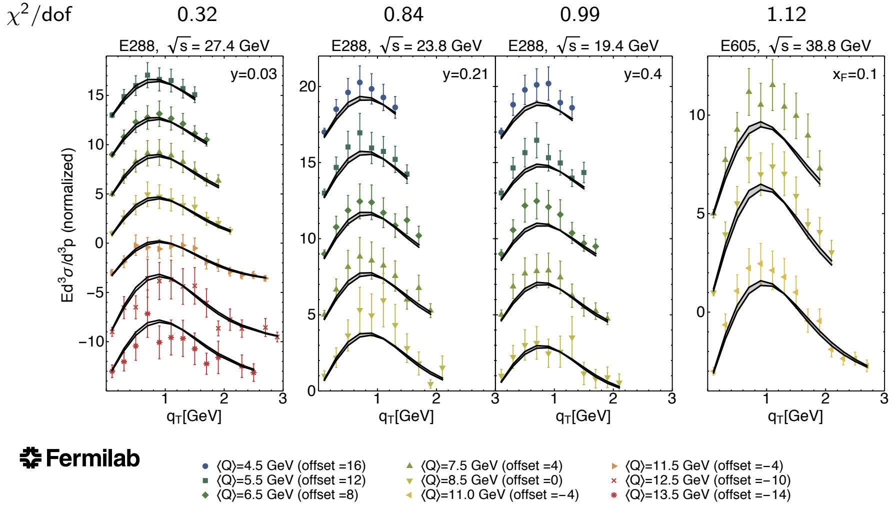
2.00

SIDIS $D \to h^+$
COMPASS data

$$\chi^2/\text{dof} = 1.01$$

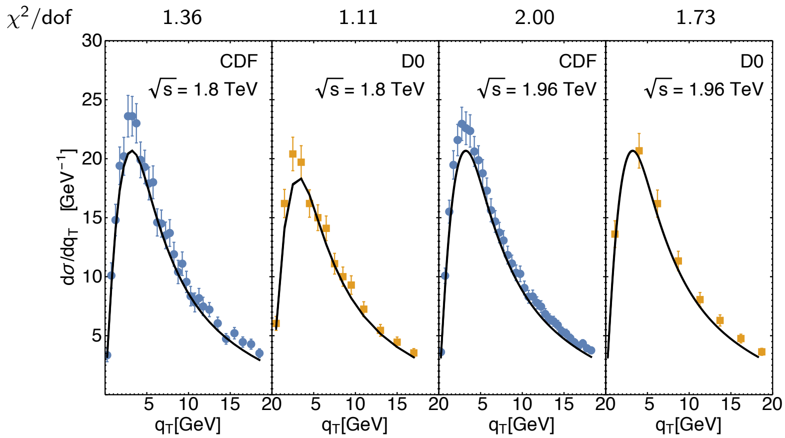


Drell-Yan data



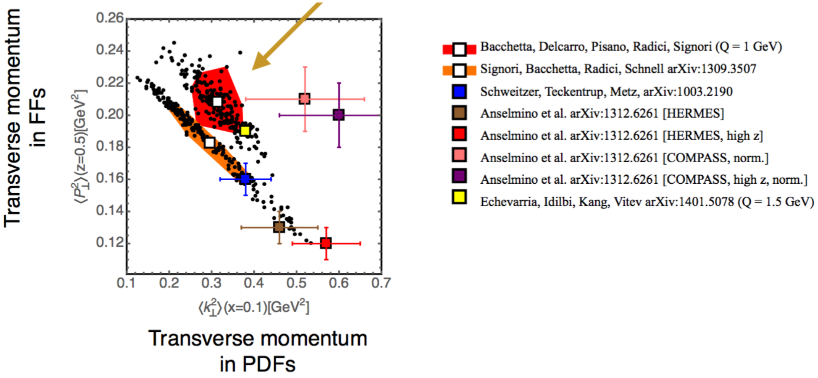
The peak is now at about 1 GeV, it was at 0.4 GeV

Z-boson production



- The peak is now at 4 GeV
- Most of the χ^2 is due to normalization

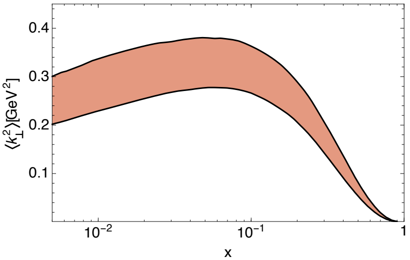
Pavia 2016 results



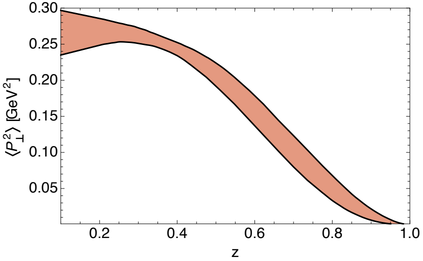
Anticorrelation between transverse momentum in TMD PDFs and in TMD FFs

Mean transverse momentum
$Q^2 = 1\ \mathrm{GeV}^2$

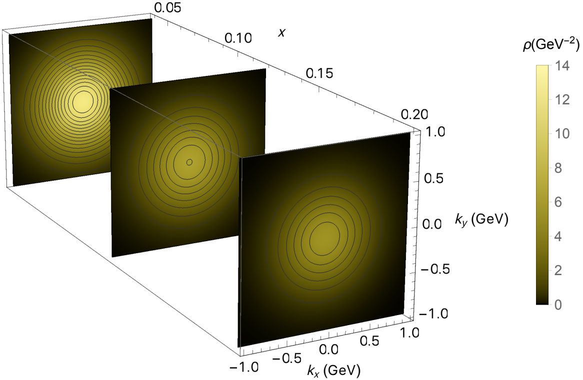
In TMD distribution functions



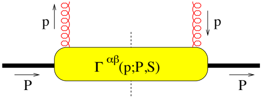
In TMD fragmentation functions



Unpolarized quark TMD at $Q^2 = 1$ GeV^2



Transverse momentum dependent gluon distributions



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

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)

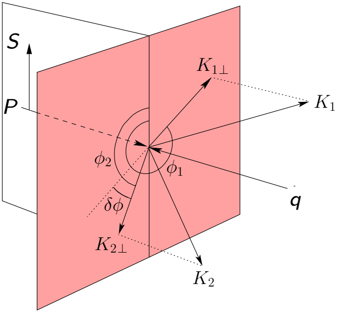
- $h_1^{\perp\, g}$: T-even distribution of linearly polarized gluons inside an unp. hadron
- h_{1T}^g, $h_{1T}^{\perp\, g}$: helicity flip distributions like h_{1T}^q, $h_{1T}^{\perp\, q}$, but T-odd, chiral even!

Transversity $h_1^q \equiv h_{1T}^q + \frac{\boldsymbol{p}_T^2}{2M_p^2}\, h_{1T}^{\perp\, q}$ survives under p_T integration, unlike h_1^g

Gluon TMDs probed directly in $e(\ell) + p(P,S) \to e(\ell') + Q(K_1) + \overline{Q}(K_2) + X$

Boer, Mulders, CP, Zhou, JHEP 1608 (2016)

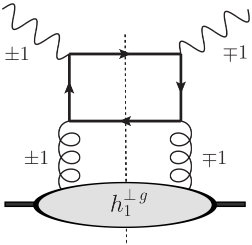
- the $Q\overline{Q}$ pair is almost back to back in the plane $\perp$ to q and P
- $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon γ^*



$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp}$$

$$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2$$

$\Longrightarrow$ Correlation limit: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$, $\quad |\boldsymbol{K}_\perp| \approx |\boldsymbol{K}_{1\perp}| \approx |\boldsymbol{K}_{2\perp}|$



$\phi_T, \phi_\perp, \phi_S$ azimuthal angles of $q_T, K_\perp, S_T$

At LO in pQCD: only $\gamma^* g \to Q\overline{Q}$ contributes

$$\mathrm{d}\sigma(\phi_S, \phi_T, \phi_\perp) = \mathrm{d}\sigma^U(\phi_T, \phi_\perp) + \mathrm{d}\sigma^T(\phi_S, \phi_T, \phi_\perp)$$

Angular structure of the unpolarized cross section for $ep \to e' Q\overline{Q}X$, $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\frac{\mathrm{d}\sigma^U}{\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}^2\boldsymbol{K}_\perp} \propto \left\{A_0^U + A_1^U \cos\phi_\perp + A_2^U \cos 2\phi_\perp\right\} f_1^g(x, \boldsymbol{q}_T^2) + \frac{\boldsymbol{q}_T^2}{M_p^2}\, h_1^{\perp\, g}(x, \boldsymbol{q}_T^2)$$
$$\times \left\{B_0^U \cos 2\phi_T + B_1^U \cos(2\phi_T - \phi_\perp) + B_2^U \cos 2(\phi_T - \phi_\perp) + B_3^U \cos(2\phi_T - 3\phi_\perp) + B_4^U \cos 2(\phi_T - 2\phi_\perp)\right\}$$

The different contributions can be isolated by defining

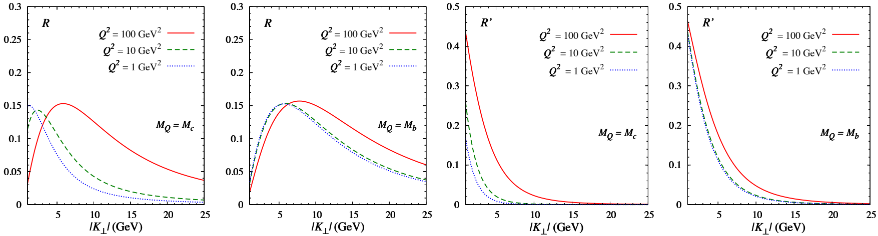
$$\langle W(\phi_\perp, \phi_T)\rangle = \frac{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\, W(\phi_\perp, \phi_T)\,\mathrm{d}\sigma}{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\, \mathrm{d}\sigma}\,, \qquad W = \cos 2\phi_T,\ \cos 2(\phi_\perp - \phi_T), \ldots$$

Positivity bound for $h_1^{\perp g}$: $$|h_1^{\perp g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2)$$

It can be used to estimate maximal values of the asymmetries

Asymmetries usually larger when Q and $\overline{Q}$ have same rapidities

Upper bounds on $R \equiv |\langle \cos 2(\phi_T - \phi_\perp) \rangle|$ and $R' \equiv |\langle \cos 2\phi_T \rangle|$ at $y = 0.01$



CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013)
Boer, Brodsky, Mulders, CP, PRL 106 (2011)

Spin asymmetries in $ep^\uparrow \to e' Q\overline{Q} X$

Angular structure of the single polarized cross section for $ep^\uparrow \to e' Q\overline{Q} X$, $\quad |\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\mathrm{d}\sigma^T \propto \sin(\phi_S - \phi_T)\Big[A_0^T + A_1^T \cos\phi_\perp + A_2^T \cos 2\phi_\perp\Big] f_{1T}^{\perp\, g} + \cos(\phi_S - \phi_T)\Big[B_0^T \sin 2\phi_T$$
$$+ B_1^T \sin(2\phi_T - \phi_\perp) + B_2^T \sin 2(\phi_T - \phi_\perp) + B_3^T \sin(2\phi_T - 3\phi_\perp) + B_4^T \sin(2\phi_T - 4\phi_\perp)\Big] h_{1T}^{\perp\, g}$$
$$+ \Big[B_0'^{\,T} \sin(\phi_S + \phi_T) + B_1'^{\,T} \sin(\phi_S + \phi_T - \phi_\perp) + B_2'^{\,T} \sin(\phi_S + \phi_T - 2\phi_\perp)$$
$$+ B_3'^{\,T} \sin(\phi_S + \phi_T - 3\phi_\perp) + B_4'^{\,T} \sin(\phi_S + \phi_T - 4\phi_\perp)\Big] h_{1T}^{g}$$

The ϕ_S dependent terms can be singled out by means of azimuthal moments A_N^W

$$A_N^{W(\phi_S,\phi_T)} \equiv 2\, \frac{\int \mathrm{d}\phi_T\, \mathrm{d}\phi_\perp\, W(\phi_S,\phi_T)\, \mathrm{d}\sigma_T(\phi_S,\, \phi_T,\, \phi_\perp)}{\int \mathrm{d}\phi_T\, \mathrm{d}\phi_\perp\, \mathrm{d}\sigma_U(\phi_T,\phi_\perp)}$$

$$A_N^{\sin(\phi_S-\phi_T)} \propto \frac{f_{1T}^{\perp\, g}}{f_1^g} \qquad A_N^{\sin(\phi_S+\phi_T)} \propto \frac{h_1^g}{f_1^g} \qquad A_N^{\sin(\phi_S-3\phi_T)} \propto \frac{h_{1T}^{\perp\, g}}{f_1^g}$$

Same modulations as in SIDIS for quark TMDs ($\phi_T \to \phi_h$)

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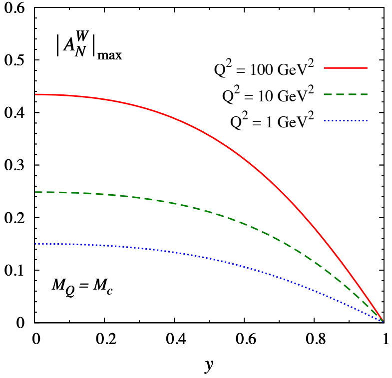
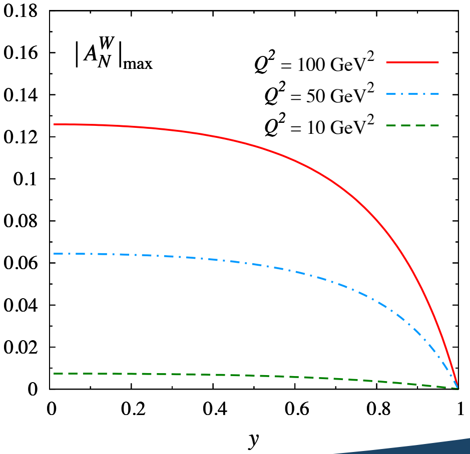
Maximal values for $|A_N^W|$, $W = \sin(\phi_S + \phi_T)$, $\sin(\phi_S - 3\phi_T)$ $(|\boldsymbol{K}_\perp| = 1$ GeV$)$



Contribution to the denominator also from $\gamma^* q \to gq$, negligible at small-x

Asymmetries much smaller than in $c\bar{c}$ case for $Q^2 \leq 10$ GeV^2

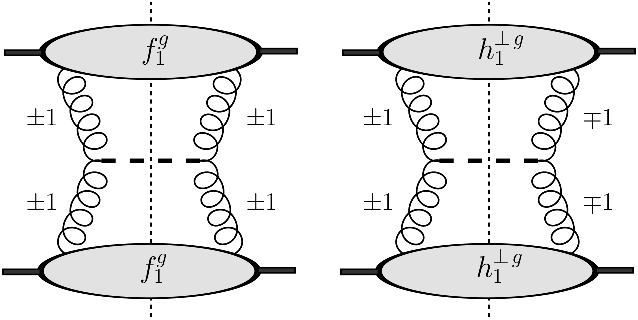
Upper bounds for A_N^W for $K_\perp \geq 4$ GeV



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

Pol. gluons affect the Higgs transverse spectrum at NNLO pQCD

Catani, Grazzini, NPB 845 (2011)



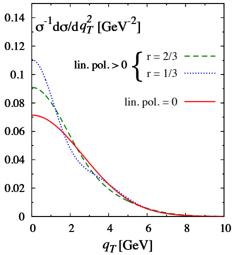
The nonperturbative distribution can be present at tree level and would contribute to Higgs production at low q_T

Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012)

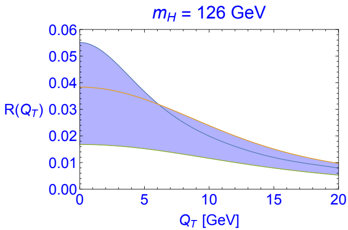
q_T-distribution of the Higgs boson

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

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)

$C = +1$ quarkonium production

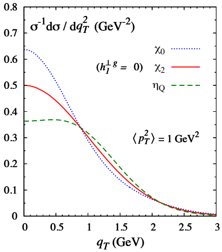
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

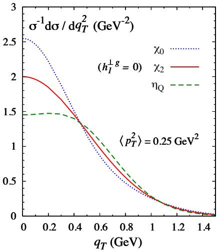
$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \, [1 - R(\boldsymbol{q}_T^2)] \qquad \text{[pseudoscalar]}$$

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

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

Boer, CP, PRD 86 (2012) 094007





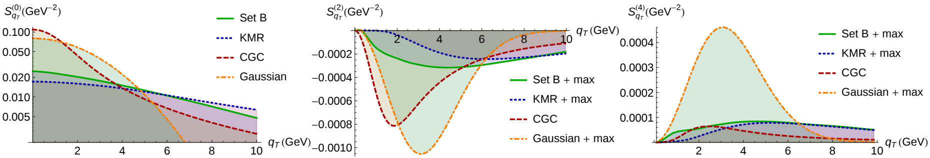
Proof of factorization at NLO for $p\,p \to \eta_Q\, X$ in the Color Singlet Model (CSM)

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

Study of $p\,p \to \eta_c\, X$ at NLO with TMD evolution (LHCb data)

Echevarria, Kasemets, Lansberg, CP, Signori, *in preparation* (2016)

$$p\,p \to J/\psi(\Upsilon) + \gamma\,X$$



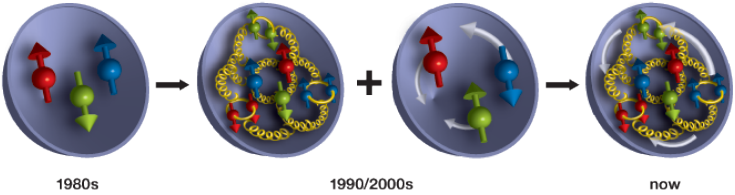
$$\frac{1}{\sigma}\,\frac{\mathrm{d}\sigma}{\mathrm{d}^2 q_T} \equiv \mathcal{S}^{(0)}_{q_T} \equiv \langle 1 \rangle_{q_T} \Longrightarrow f_1^g \otimes f_1^g$$

$$\mathcal{S}^{(2)}_{q_T} \equiv \langle \cos 2\phi \rangle_{q_T} \Longrightarrow f_1^g \otimes h_1^{\perp g}$$

$$\mathcal{S}^{(4)}_{q_T} \equiv \langle \cos 4\phi \rangle_{q_T} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014)

Conclusions



- Much progress in our understanding of the nucleon, however it still remains a mysterious and fascinating object. Evidence for going beyond 1D picture
- Transverse momentum distributions provide a 3D description of the partonic structure of the nucleon; interplay between theory and experiment
- Unpolarized quark TMDs extracted from several hundred data points
- Waiting for new data from COMPASS, JLAB-12, RHIC, and eventually EIC
- Phenomenology and theory issues:
  factorization breaking, TMD evolution, nonperturbative inputs