Gluon TMDs (very low-x)

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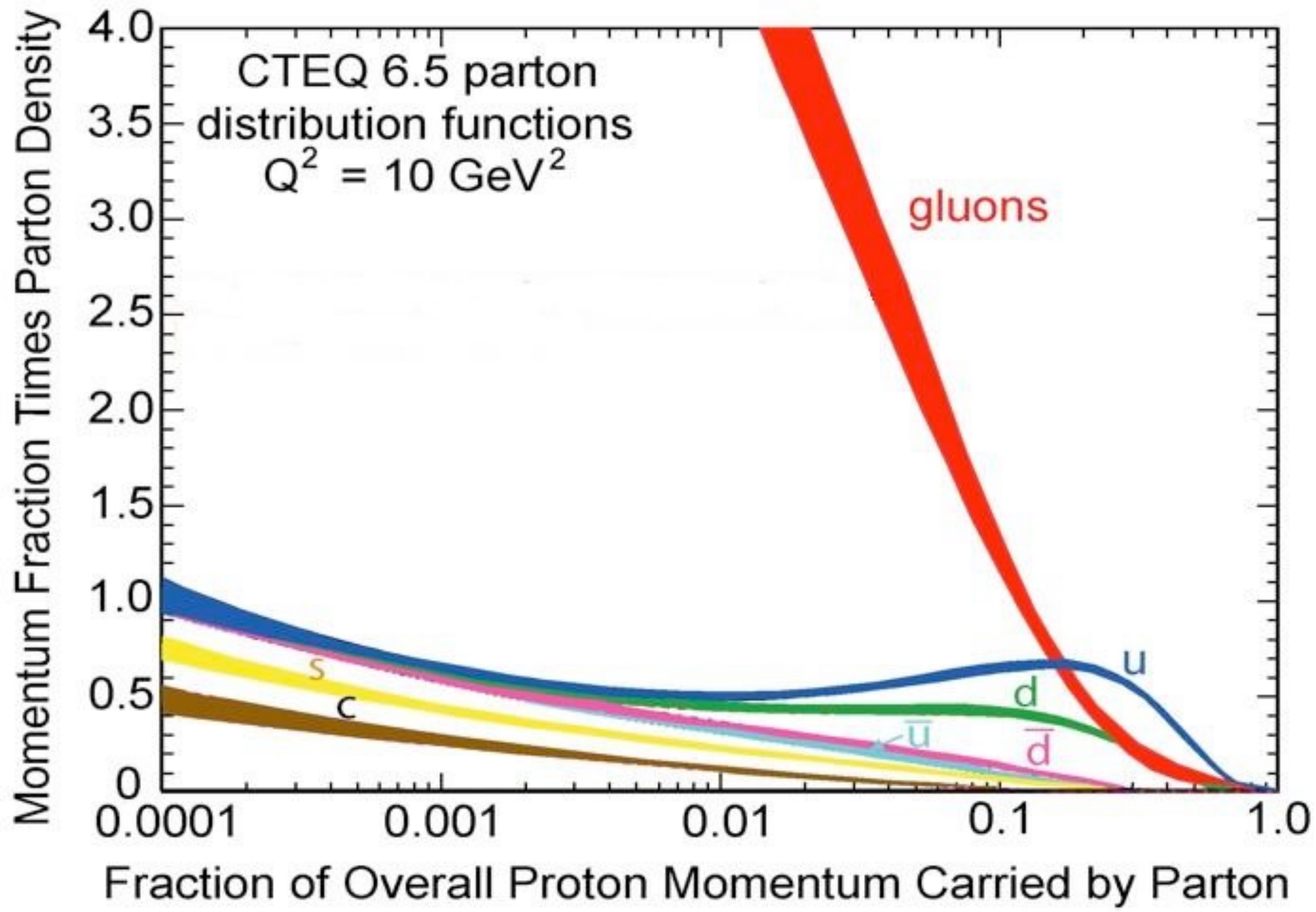
3D Parton Distributions: path to the LHC

Frascati, November 30, 2016

university of groningen

Partons at small x

Gluons dominate at high center of mass energy s, where the gluons carry a small fraction of the proton momentum: $x \approx Q^2/s \ll 1$



At small x it becomes natural to consider the transverse momentum dependence

TMD = *transverse momentum dependent* parton distribution

Because of the additional k_T dependence there are more TMDs than collinear pdfs

Gluons TMDs

The gluon correlator:

$$\Gamma_g^{\mu\nu[\mathcal{U},\mathcal{U}']}(x,k_T) \equiv \mathrm{F.T.}\langle P|\mathrm{Tr}_c\left[F^{+\nu}(0)\,\mathcal{U}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}'_{[\xi,0]}\right]|P\rangle$$

For unpolarized protons:

$$\Gamma_U^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{x}{2}\left\{-g_T^{\mu\nu} f_1^g(x,\boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{p}_T^2}{2M_p^2}\right) h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)\right\}$$

unpolarized gluon TMD

linearly polarized gluon TMD

Gluons inside *unpolarized* protons can be polarized!

For transversely polarized protons:

gluon Sivers TMD

$$\Gamma_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{x}{2}\left\{g_T^{\mu\nu}\frac{\epsilon_T^{\rho\sigma}p_{T\rho}S_{T\sigma}}{M_p} f_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2) + \ldots\right\}$$

[Mulders, Rodrigues '01]

Process dependence

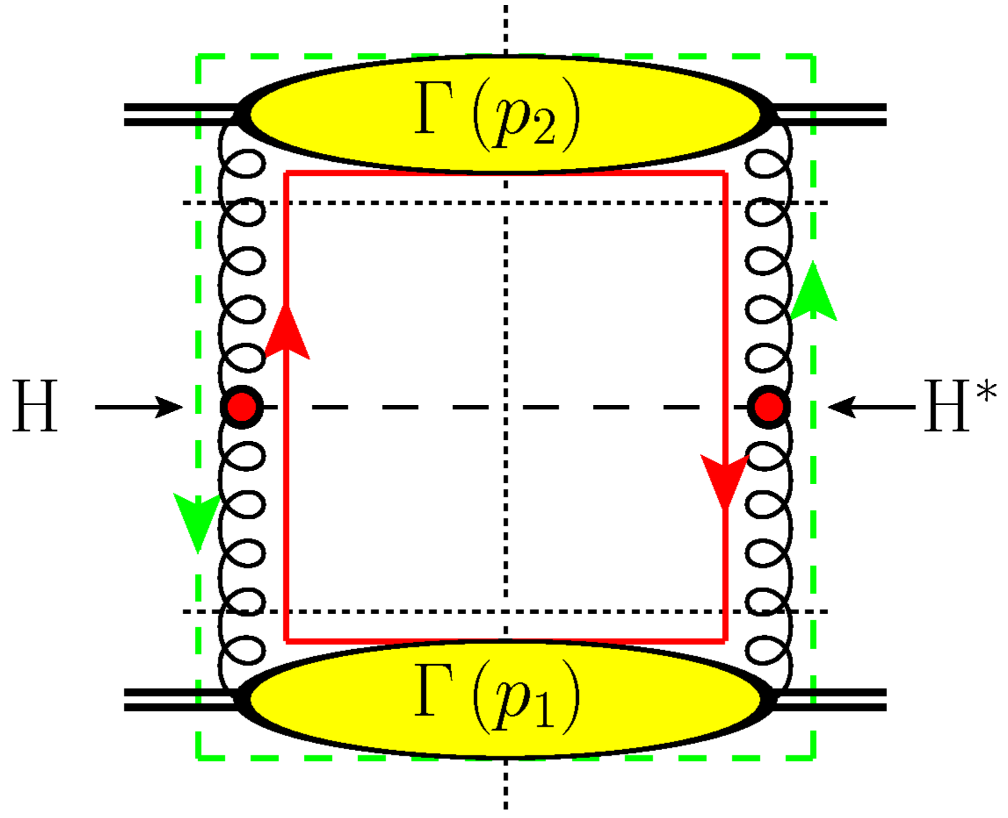
Factorization and color flow

Theoretical description of high-energy scattering cross sections is based on **factorization** in perturbative partonic hard scattering factors (H) and nonperturbative hadronic correlators (Φ,Γ,Δ), i.e. parton distributions

Higgs production: $pp \to HX$

Color treatment is simple at high energies: separate traces, not dependent on kinematics

But in the actual process there are no colored final states and there are many soft gluons exchanged to balance the color



This cartoon version of the color flow works fine in most cases, when collinear factorization applies

In TMD factorization the color flow in a process leads to distinct correlators

Process dependence of gluon TMDs

$$\Gamma_g^{\mu\nu[\mathcal{U},\mathcal{U}']}(x,k_T) \equiv \mathrm{F.T.}\langle P|\mathrm{Tr}_c\left[F^{+\nu}(0)\,\mathcal{U}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}'_{[\xi,0]}\right]|P\rangle$$

$$\mathcal{U}_{\mathcal{C}}[0,\xi] = \mathcal{P}\exp\left(-ig\int_{\mathcal{C}[0,\xi]} ds_\mu\,A^\mu(s)\right) \qquad \xi = [0^+,\xi^-,\boldsymbol{\xi}_T]$$

The gauge links are process dependent, affecting even the unpolarized gluon TMDs as was first realized in a small-x context

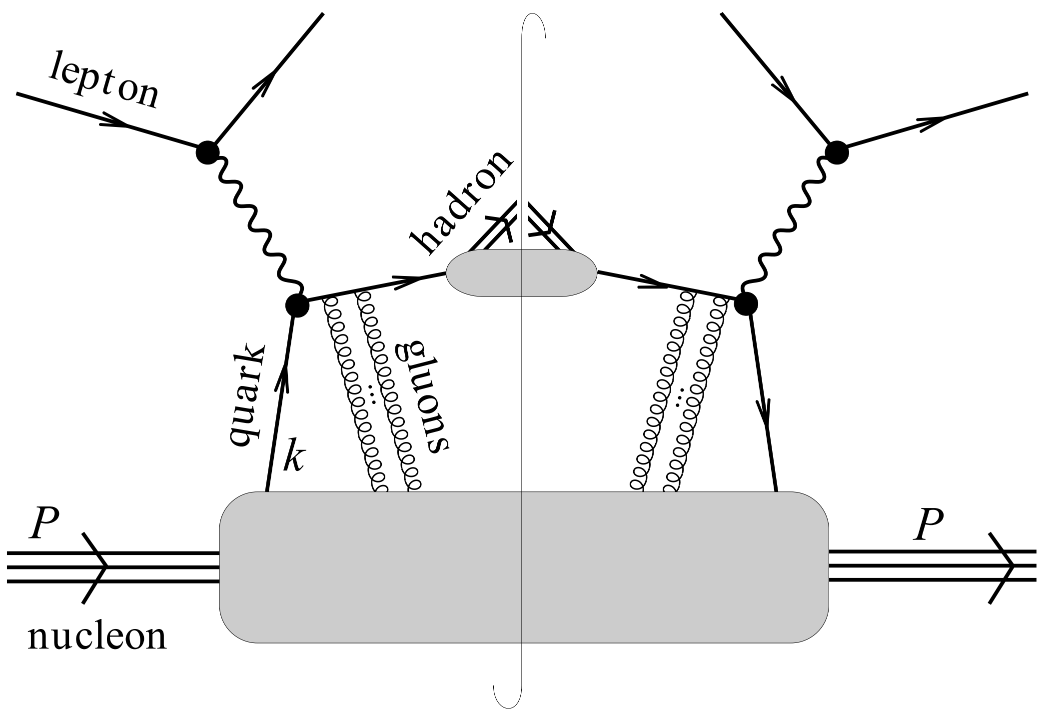
Dominguez, Marquet, Xiao, Yuan, 2011

Kharzeev, Kovchegov & Tuchin (2003): ``A tale of two gluon distributions"
They noted there are 2 distinct but equally valid definitions for the small-x gluon distribution: the Weizsäcker-Williams (WW) and the dipole (DP) distribution

KKT: “cannot offer any simple physical explanation of this paradox”

The explanation turns out to be in the process dependence of the gluon distribution, in other words, its sensitivity to the initial and/or final state interactions (ISI/FSI) in a process, without them WW and DP would be the same

Initial and final state interactions



summation of all gluon rescatterings leads to path-ordered exponentials in correlators

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

$$\Phi \propto \langle P|\overline{\psi}(0)\mathcal{L}_{\mathcal{C}}[0,\xi]\psi(\xi)|P\rangle$$

Efremov & Radyushkin, Theor. Math. Phys. 44 ('81) 774

Resulting Wilson lines depend on whether the color is incoming or outgoing

[Collins & Soper, 1983; D.B. & Mulders, 2000; Brodsky, Hwang & Schmidt, 2002; Collins, 2002; Belitsky, X. Ji & F. Yuan, 2003; D.B., Mulders & Pijlman, 2003]

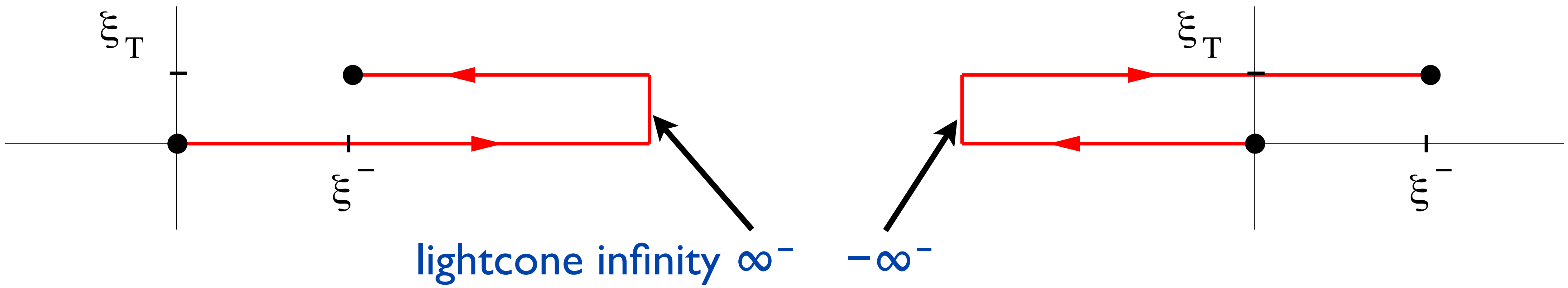
This does not automatically imply that the ISI and/or FSI affect observables, but it turns out that they do in certain cases, for example, Sivers effect asymmetries

[Brodsky, Hwang & Schmidt, 2002; Collins, 2002; Belitsky, Ji & Yuan, 2003]

Process dependence of Sivers TMDs

SIDIS DY

FSI lead to a future pointing Wilson line (+ link), whereas ISI to past pointing (− link)



One can use parity and time reversal invariance to relate these

$$f_{1T}^{\perp q[\mathrm{SIDIS}]}(x, k_T^2) = -f_{1T}^{\perp q[\mathrm{DY}]}(x, k_T^2)$$ [Collins '02]

A similar sign change relation for gluon Sivers functions holds, but due to the appearance of two gauge links, there are more possibilities

Sign change relation for **gluon** Sivers TMD

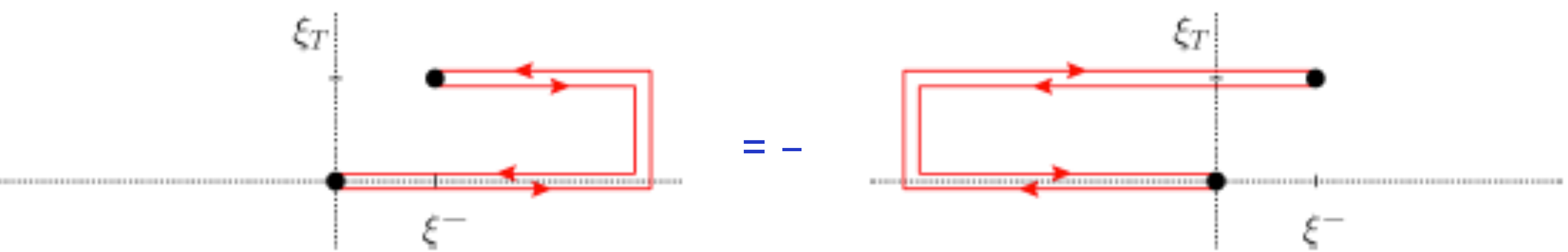
$$e\,p^{\uparrow} \to e'\,Q\bar{Q}\,X$$ $\gamma^*\,g \to Q\bar{Q}$ probes [+,+]

Qiu, Schlegel, Vogelsang, 2011

$$p^{\uparrow}\,p \to \gamma\,\gamma\,X$$

In the kinematic regime where pair rapidity is central, one effectively selects the subprocess:

$g\,g \to \gamma\,\gamma$ probes [−,−]



$$f_{1T}^{\perp\,g\,[e\,p^{\uparrow}\to e'\,Q\,\overline{Q}\,X]}(x,p_T^2) = -f_{1T}^{\perp\,g\,[p^{\uparrow}\,p\to\gamma\,\gamma\,X]}(x,p_T^2)$$

D.B., Mulders, Pisano, Zhou, 2016

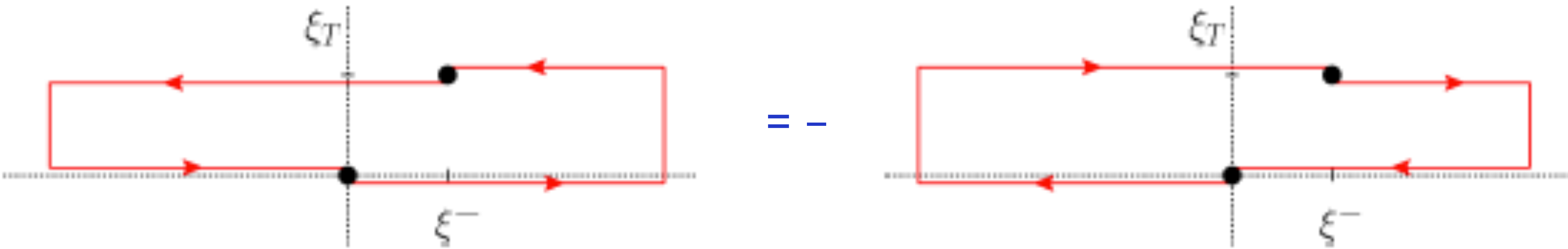
Important role for EIC

f and d type gluon Sivers TMD

$e\, p^{\uparrow} \to e'\, Q\bar{Q}\, X$ $\gamma^*\, g \to Q\bar{Q}$ probes [+,+]

$p^{\uparrow}\, p \to \gamma\, \text{jet}\, X$

In the kinematic regime where gluons in the polarized proton dominate, one effectively selects the subprocess: $g\, q \to \gamma\, q$ probes [+,−]



These processes probe 2 distinct, **independent** gluon Sivers functions

Related to antisymmetric (f^{abc}) and symmetric (d^{abc}) color structures

Bomhof, Mulders, 2007; Buffing, Mukherjee, Mulders, 2013

Conclusion: gluon Sivers TMD studies at EIC and at RHIC or AFTER@LHC can be related or complementary, depending on the processes considered

D.B., Lorcé, Pisano & Zhou, arXiv:1504.04332

Unpolarized gluon TMDs at small x

WW vs DP

For most processes of interest there are 2 relevant unpolarized gluon distributions

Dominguez, Marquet, Xiao, Yuan, 2011

$$xG^{(1)}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \langle P|\mathrm{Tr}\left[F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[+]\dagger}F^{+i}(0)\mathcal{U}^{[+]}\right]|P\rangle \qquad [+,+]$$

$$xG^{(2)}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \langle P|\mathrm{Tr}\left[F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[-]\dagger}F^{+i}(0)\mathcal{U}^{[+]}\right]|P\rangle \qquad [+,-]$$

For unpolarized gluons [+,+] = [−,−] and [+,−] = [−,+]

At small x the two correspond to the Weizsäcker-Williams (WW) and dipole (DP) distributions, which are generally different in magnitude and width:

$$xG^{(1)}(x,k_\perp) = -\frac{2}{\alpha_S}\int \frac{d^2v}{(2\pi)^2}\frac{d^2v'}{(2\pi)^2}\, e^{-ik_\perp\cdot(v-v')}\left\langle \mathrm{Tr}\left[\partial_i U(v)\right]U^\dagger(v')\left[\partial_i U(v')\right]U^\dagger(v)\right\rangle_{x_g} \qquad \text{WW}$$

$$xG^{(2)}(x,q_\perp) = \frac{q_\perp^2 N_c}{2\pi^2\alpha_s} S_\perp \int \frac{d^2r_\perp}{(2\pi)^2} e^{-iq_\perp\cdot r_\perp}\frac{1}{N_c}\left\langle \mathrm{Tr}U(0)U^\dagger(r_\perp)\right\rangle_{x_g} \qquad \text{DP}$$

Different processes probe one or the other or a mixture, so this can be tested

MV model

In the MV model one may not notice the origin for the difference between WW and DP, because the two TMDs become related:

$$xG_g^{(2)}(x,q_\perp) \overset{\text{MV}}{\propto} q_\perp^2 \nabla_{q_\perp}^2 \, xG_g^{(1)}(x,q_\perp)$$

Processes involving $G^{(1)}$ (WW) [+,+] in the MV model can be expressed in terms of $G^{(2)} \sim C(k_\perp)$, e.g.

$$\gamma\, A \to Q\bar{Q}\, X$$

Gelis, Peshier, 2002

$$\frac{d\sigma_T}{dy\, dk_\perp} = \pi R^2 \frac{2N_c(Z\alpha)^2}{3\pi^3} \ln\Big(\frac{\gamma}{2mR}\Big) k_\perp C(k_\perp) \times \left\{1 + \frac{4(k_\perp^2 - m^2)}{k_\perp\sqrt{k_\perp^2+4m^2}} \operatorname{arcth} \frac{k_\perp}{\sqrt{k_\perp^2+4m^2}}\right\}$$

$$C(k_\perp) = \int d^2x_\perp\, e^{ik_\perp\cdot x_\perp} \langle U(0)U^\dagger(x_\perp)\rangle$$

Heavy quark pair production in DIS probes the WW distribution, like pp→Higgs X

For general x expressions, see Pisano, D.B., Brodsky, Buffing, Mulders, 2013

WW vs DP

Selection of processes that probe the WW or DP unpolarized gluon TMD:

	DIS	DY	SIDIS	$pA \to \gamma\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$f_1^{g\,[+,+]}$ (WW)	$\times$	$\times$	$\times$	$\times$	$\surd$	$\surd$	$\surd$
$f_1^{g\,[+,-]}$ (DP)	$\surd$	$\surd$	$\surd$	$\surd$	$\times$	$\times$	$\times$

Dijet production in pA probes a combination of 6 distinct unpolarized gluon TMDs
In the large N_c limit it probes a combination of DP and WW functions

Akcakaya, Schäfer, Zhou, 2013; Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren, 2015

Dijet production in pA generally suffers from factorization breaking contributions

Collins, Qiu, 2007; Rogers, Mulders, 2010

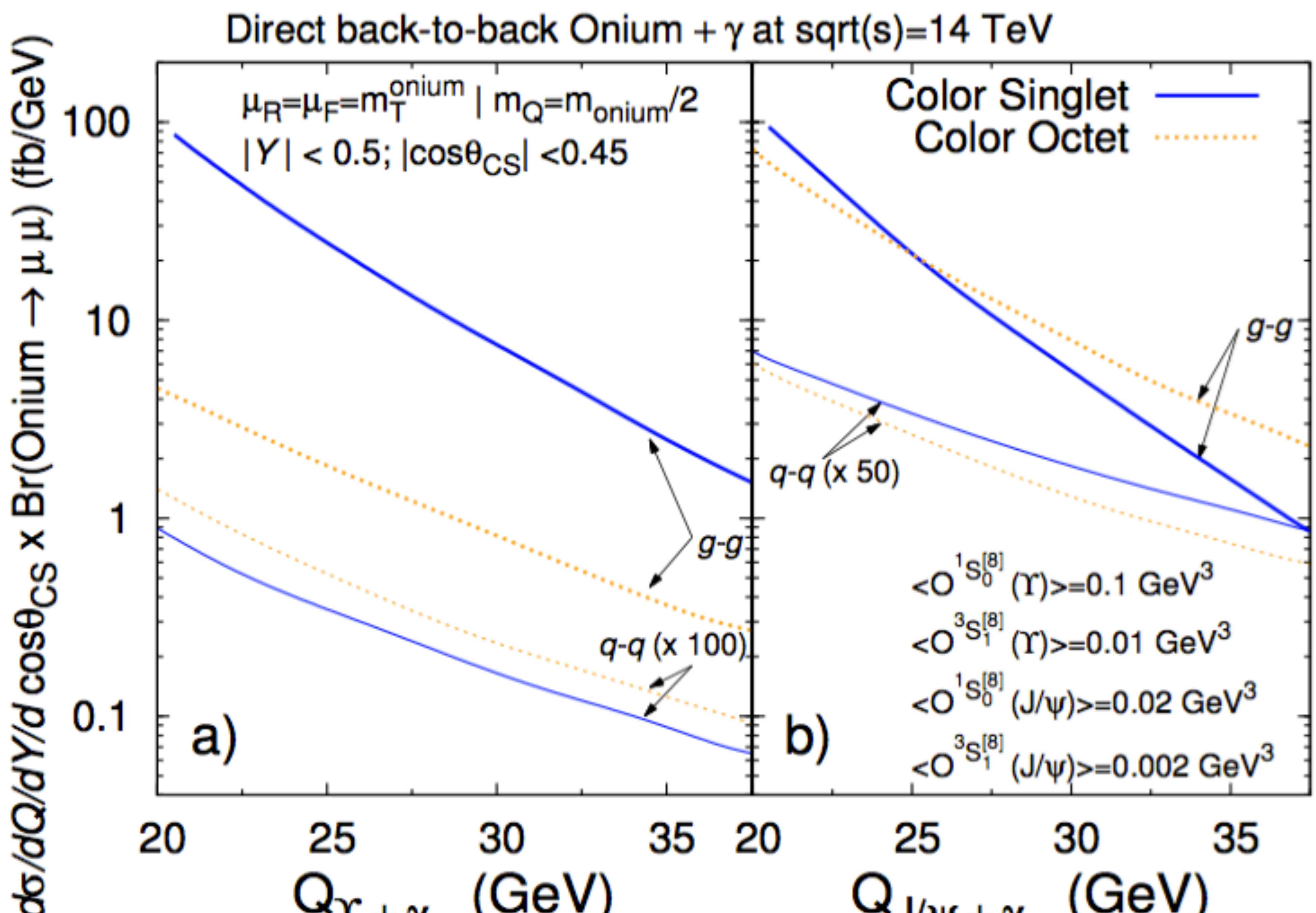
Single color singlet (CS) J/ψ or ϒ production from two gluons is not allowed by the Landau-Yang theorem, while color octet (CO) production involves a more complicated link structure. C-even (pseudo-)scalar quarkonium production is easier

D.B., Pisano, 2012

CS vs CO

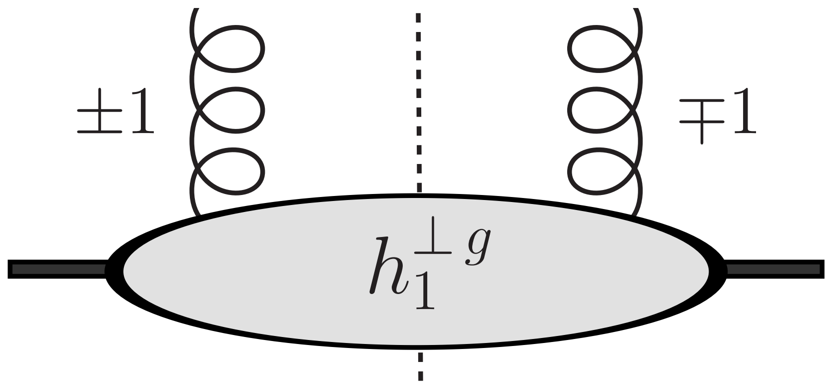
In Υ+γ production the color singlet contribution dominates and in J/ψ+γ production for a specific range of invariant mass of the pair

den Dunnen, Lansberg, Pisano, Schlegel, 2014



Linearly polarized gluons in unpolarized hadrons at small x

Gluon polarization inside unpolarized protons



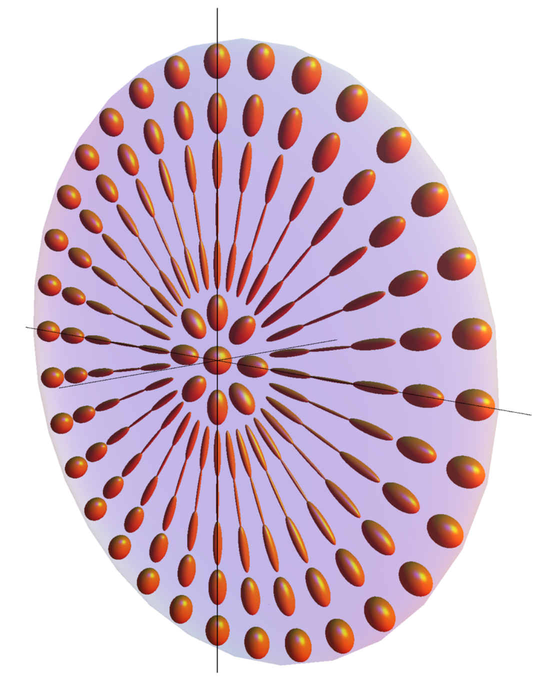
an interference between ±1 helicity gluon states

Linearly polarized gluons can exist in **unpolarized** hadrons

[Mulders, Rodrigues, 2001]

It requires nonzero transverse momentum: TMD

For $h_1^{\perp g} > 0$ gluons prefer to be polarized along k_T, with a $\cos 2\phi$ distribution of linear polarization around it, where $\phi = \angle(k_T, \varepsilon_T)$



This TMD is k_T-even, chiral-even and T-even:

$$\Gamma_U^{\mu\nu}(x, \boldsymbol{p}_T) = \frac{x}{2} \left\{ -g_T^{\mu\nu}\, f_1^g(x, \boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu} \frac{\boldsymbol{p}_T^2}{2M_p^2} \right) h_1^{\perp g}(x, \boldsymbol{p}_T^2) \right\}$$

For linearly polarized gluons also [+,+] = [−,−] and [+,−] = [−,+]

Linear gluon polarization at small x

$h_1^{\perp g}$ is more difficult to extract, as it cannot be probed in DIS, DY, SIDIS, nor in inclusive hadron or γ+jet production in pp or pA collisions

Selection of processes that probe the WW or DP linearly polarized gluon TMD:

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp\,g\,[+,+]}$ (WW)	$\surd$	$\times$	$\surd$	$\surd$	$\surd$
$h_1^{\perp\,g\,[+,-]}$ (DP)	$\times$	$\surd$	$\times$	$\times$	$\times$

Higgs and $0^{\pm+}$ quarkonium production allows to measure the linear gluon polarization using the angular independent p_T distribution

All other suggestions use angular modulations

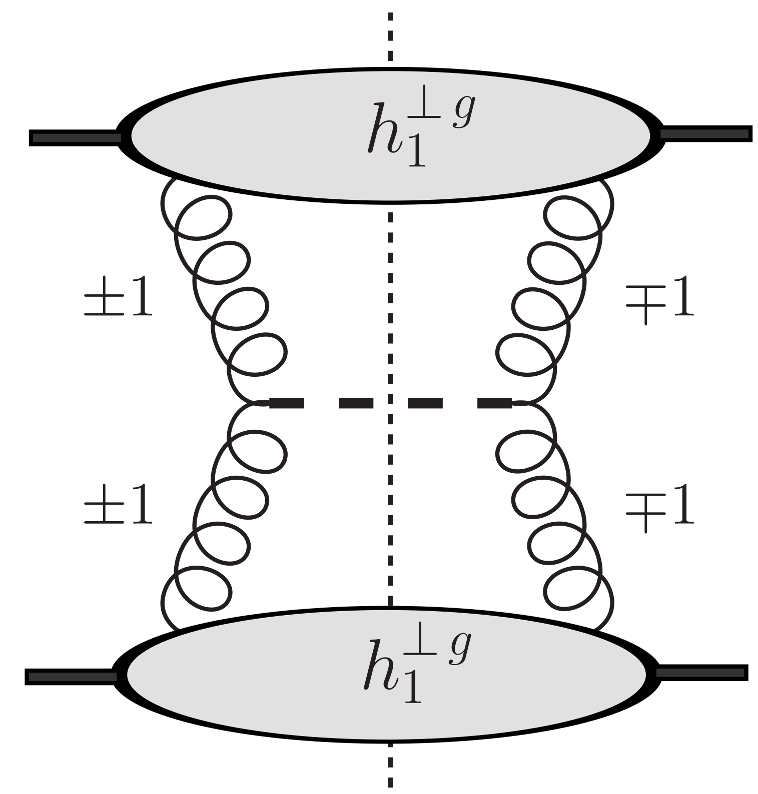
EIC and RHIC/LHC can probe same $h_1^{\perp g}$

Qiu, Schlegel, Vogelsang, 2011; Jian Zhou , 2016; D.B., Brodsky, Pisano, Mulders, 2011; D.B., Pisano, 2012; Sun, Xiao, Yuan, 2011; D.B., den Dunnen, Pisano, Schlegel, Vogelsang, 2012; den Dunnen, Lansberg, Piano, Schlegel, 2014

Linear gluon polarization in pp→HX

$h_1^{\perp g}$ affects Higgs production at the LHC

Boer, Den Dunnen, Pisano, Schlegel, Vogelsang, PRL 2012



The LHC is actually a *polarized* gluon collider

It remains to be seen whether this can be exploited

The relative effect of linearly polarized gluons:

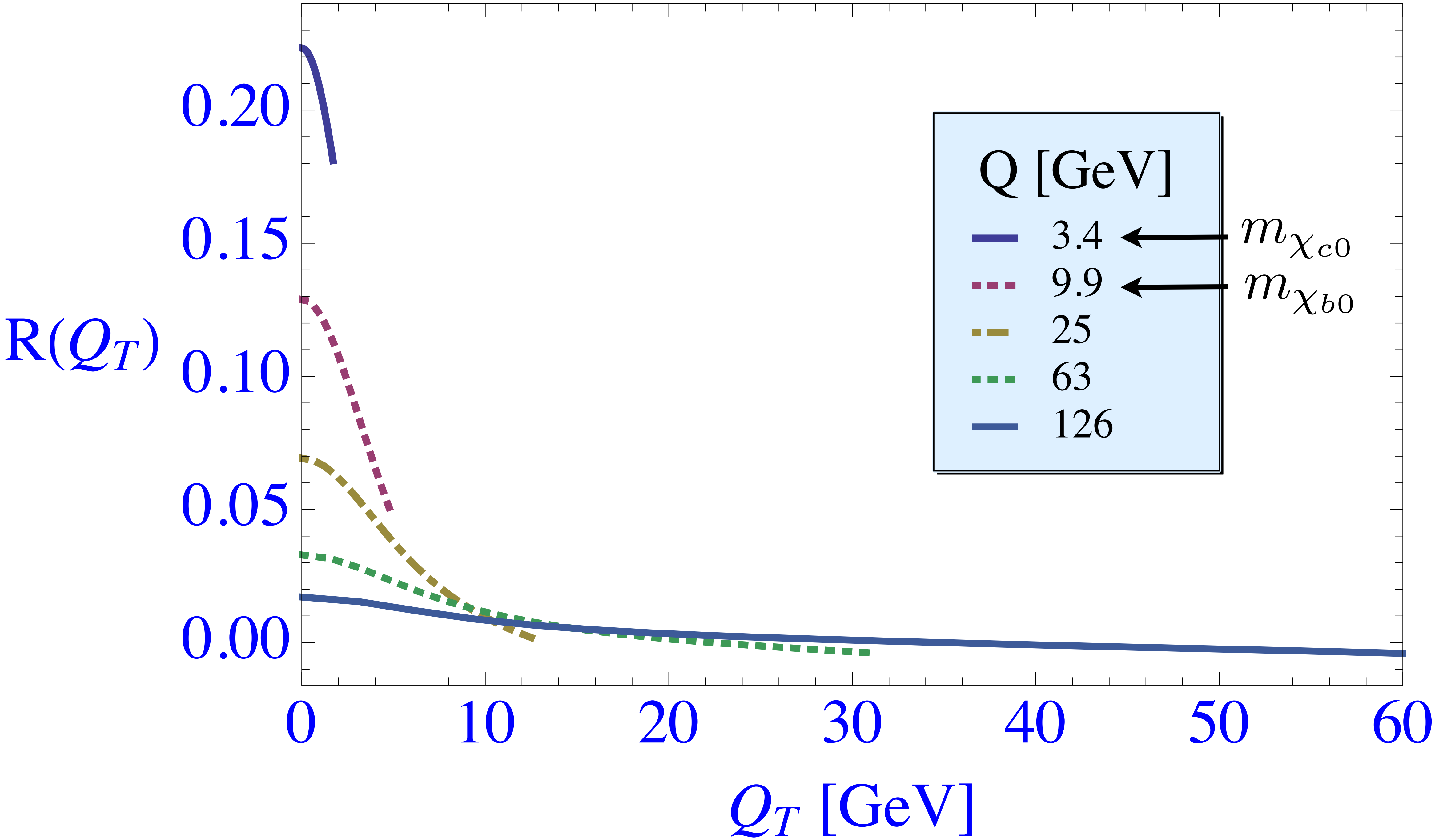
$$\mathcal{R}(Q_T) \equiv \frac{\mathcal{C}[w_H\, h_1^{\perp g}\, h_1^{\perp g}]}{\mathcal{C}[f_1^g\, f_1^g]}$$

$$w_H = \frac{(\boldsymbol{p}_T \cdot \boldsymbol{k}_T)^2 - \frac{1}{2}\boldsymbol{p}_T^2 \boldsymbol{k}_T^2}{2M^4}$$

TMD evolution suppresses this ratio

D.B. & den Dunnen, 2014

Color singlet scalar production

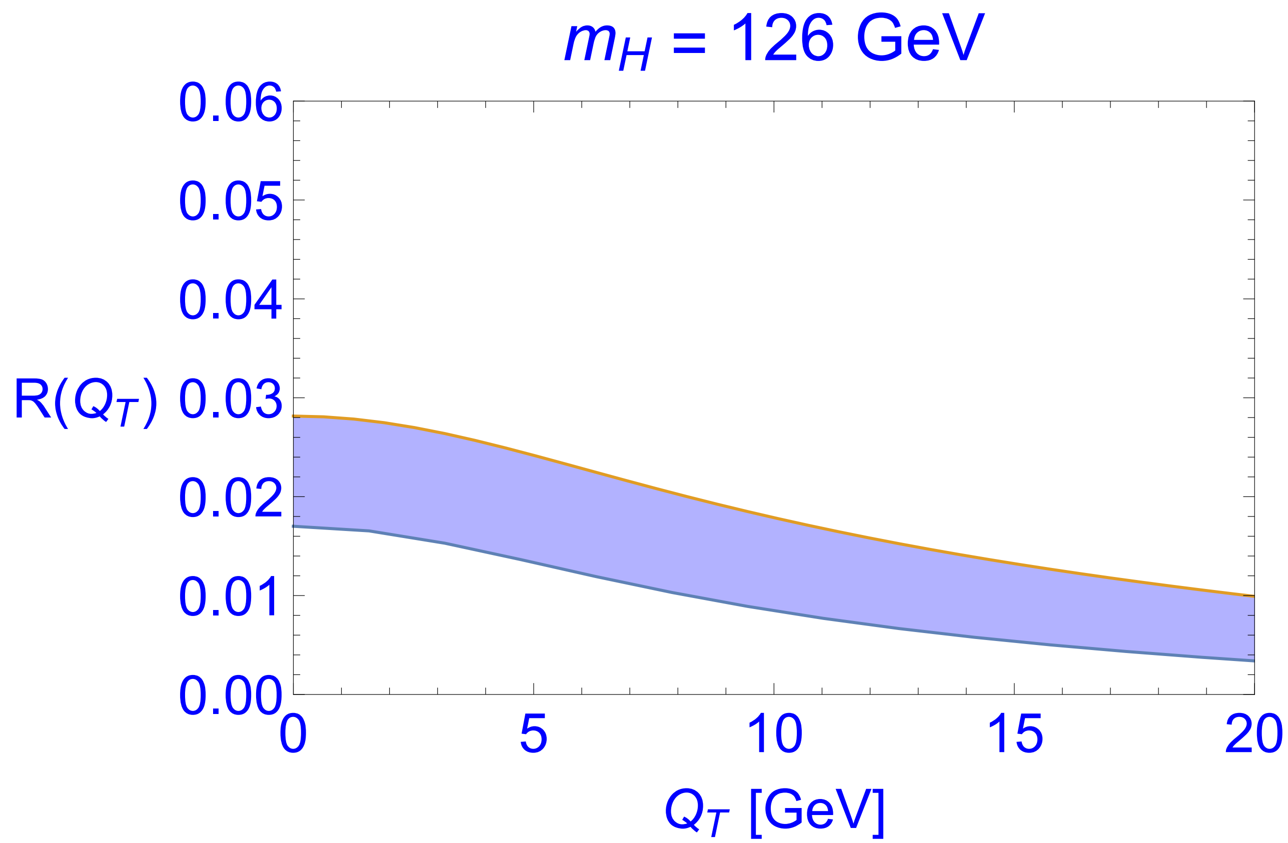


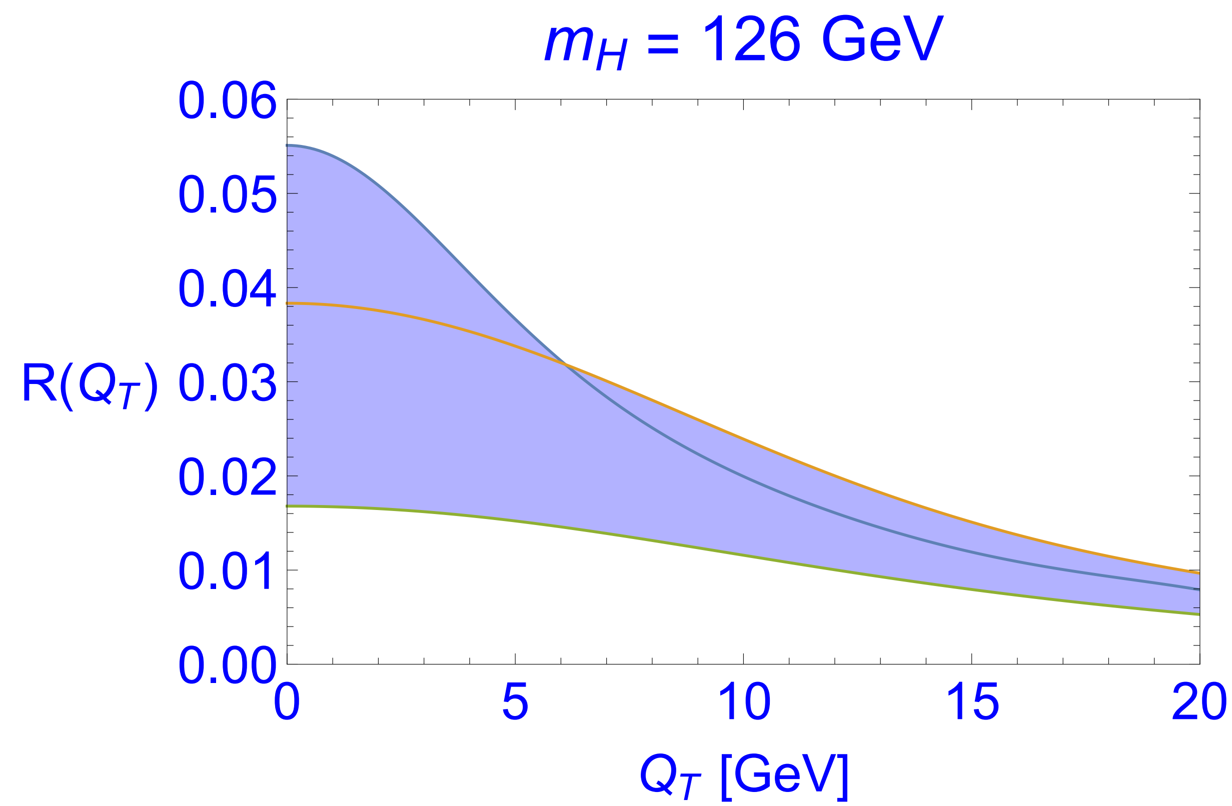
Quantum corrections imply that the effect of linear gluon polarization decreases with the mass of the scalar produced as: $Q^{-0.85}$

D.B. & den Dunnen, 2014

Conclusion: in Higgs production linear gluon polarization contributes at few % level

Range of predictions





Boer & den Dunnen, 2014

Echevarria, Kasemets, Mulders, Pisano, 2015

Left: variation of the nonperturbative input and of the large Q_T behavior

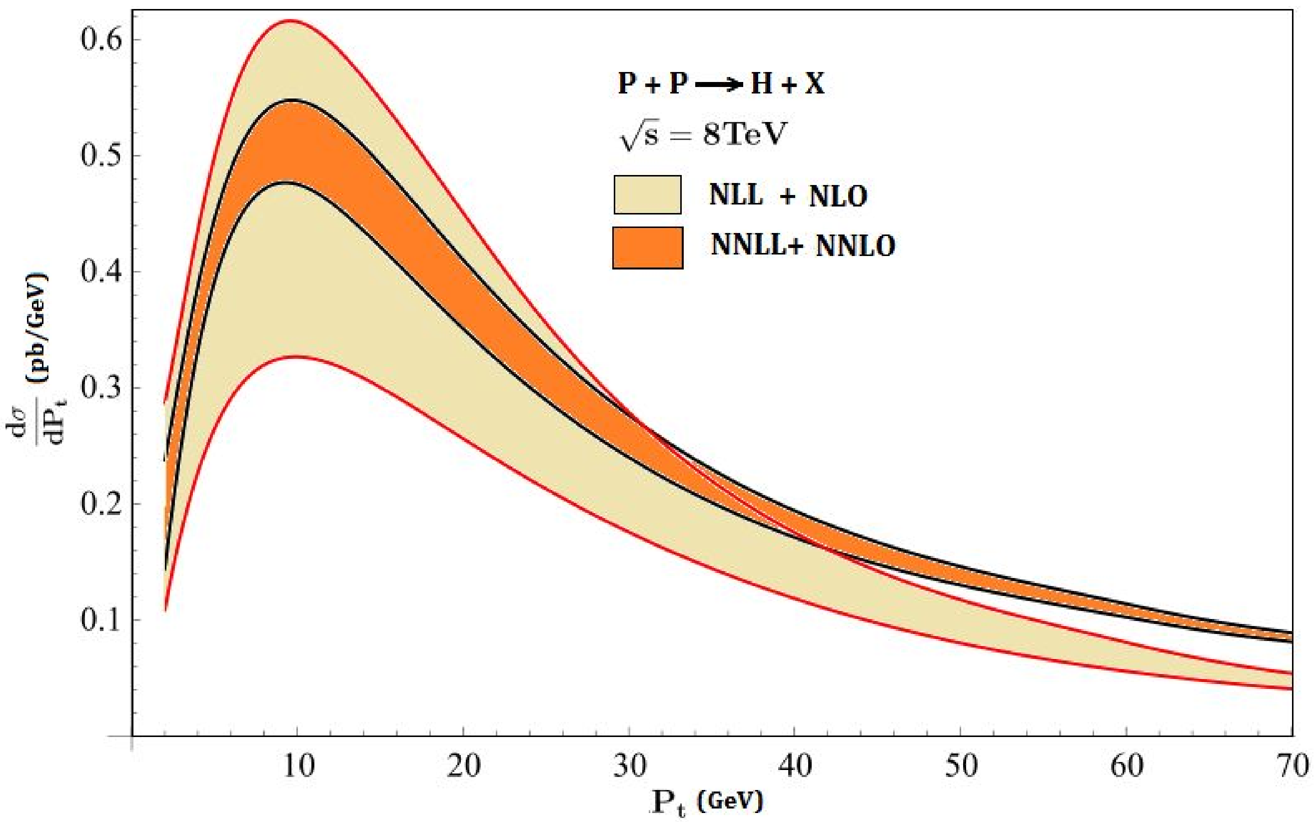
Right: variation of the nonperturbative input and the renormalization scale

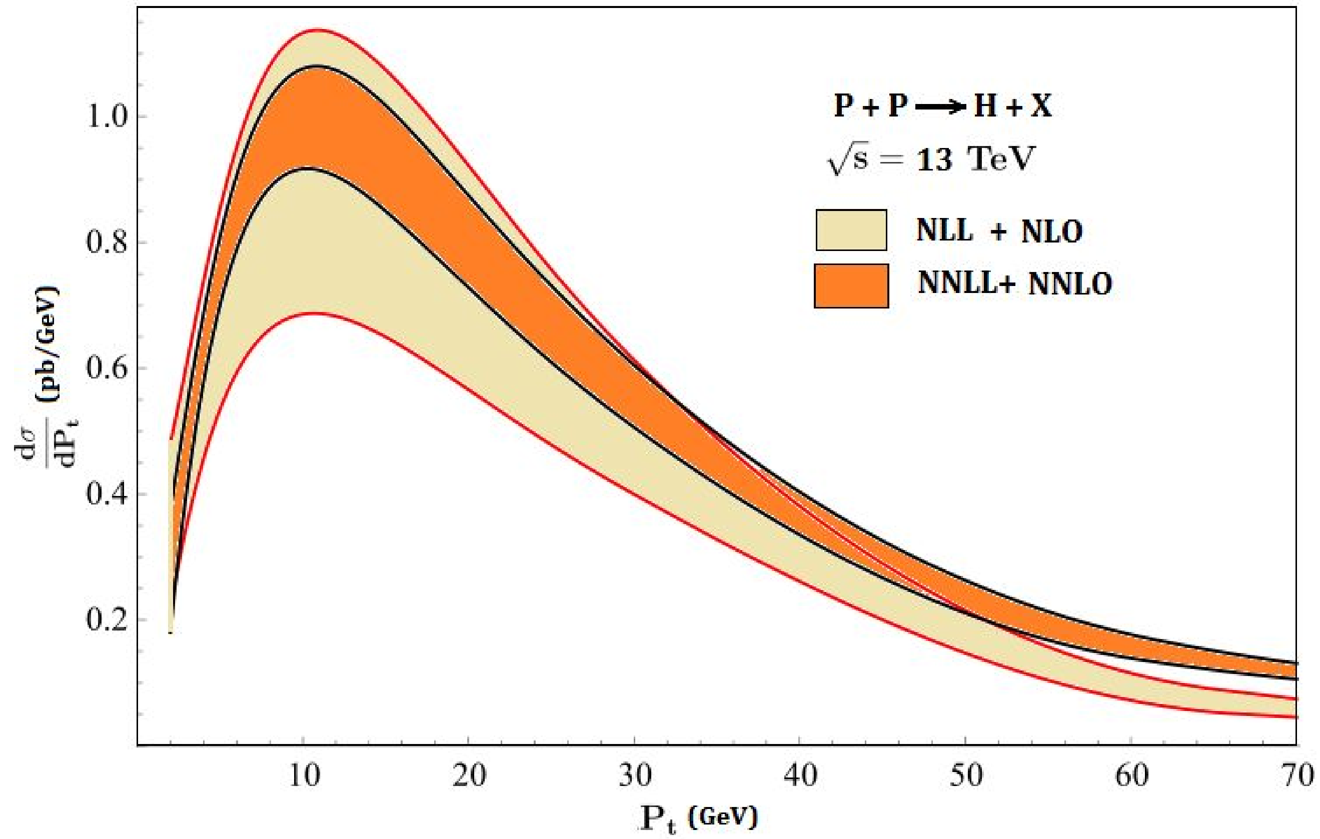
Conclusions:

- effect of linear gluon polarization in Higgs production on the order of 2-5%
- extraction of $h_1^{\perp g}$ from Higgs production may be too challenging

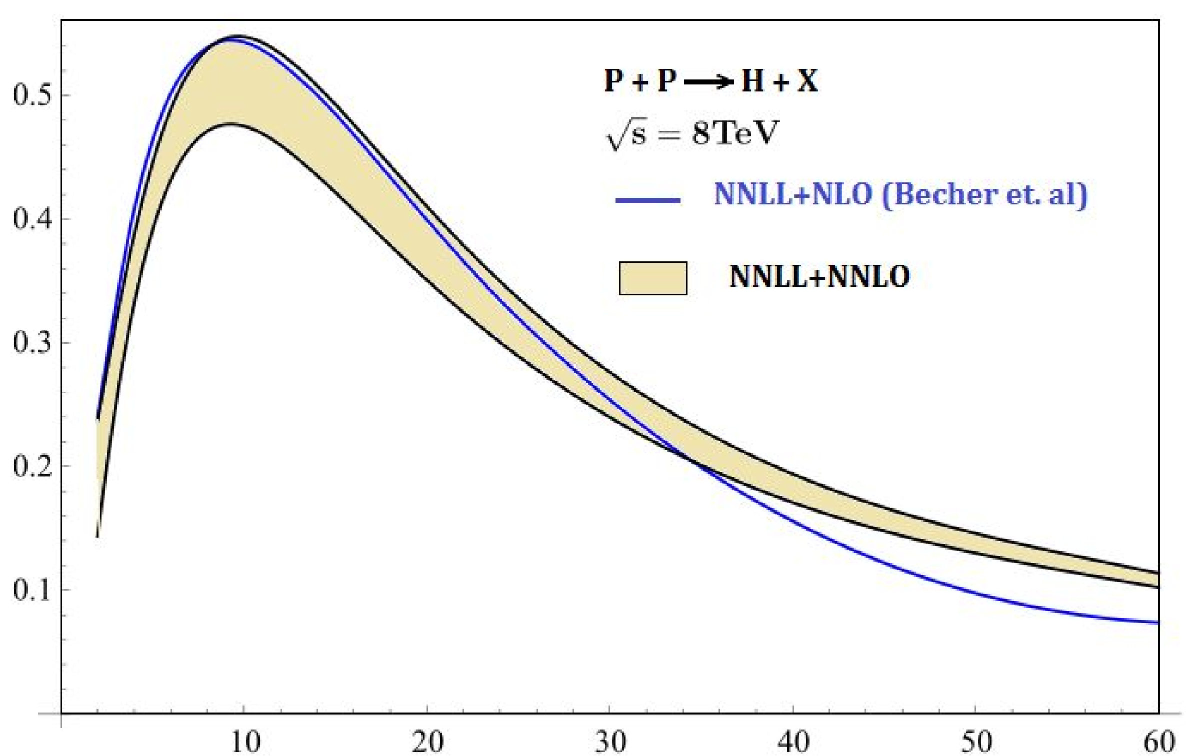
Effects larger at smaller Q ($0^{\pm +}$ quarkonia) and at small x (plots are for x ~ 0.016)

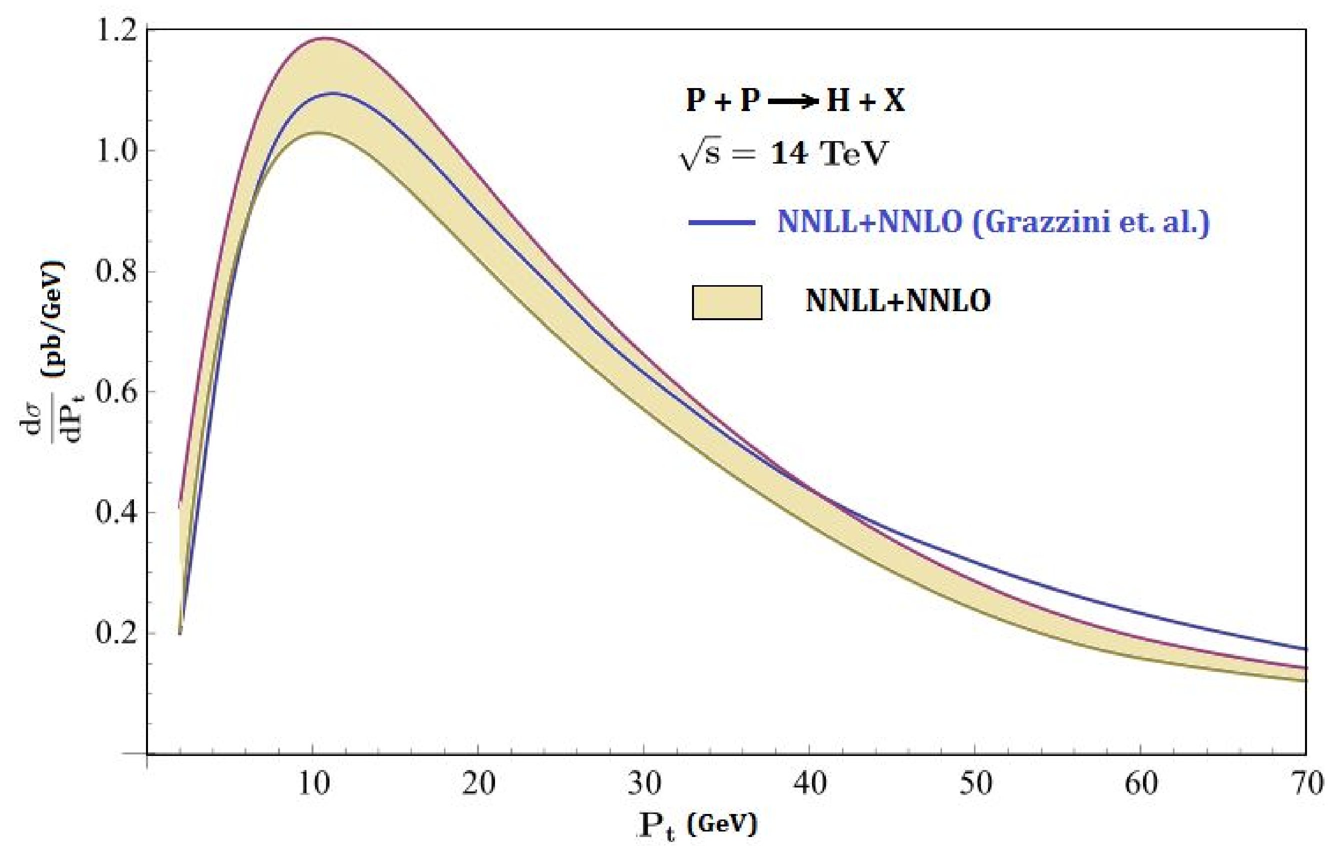
Perturbative state-of-the-art





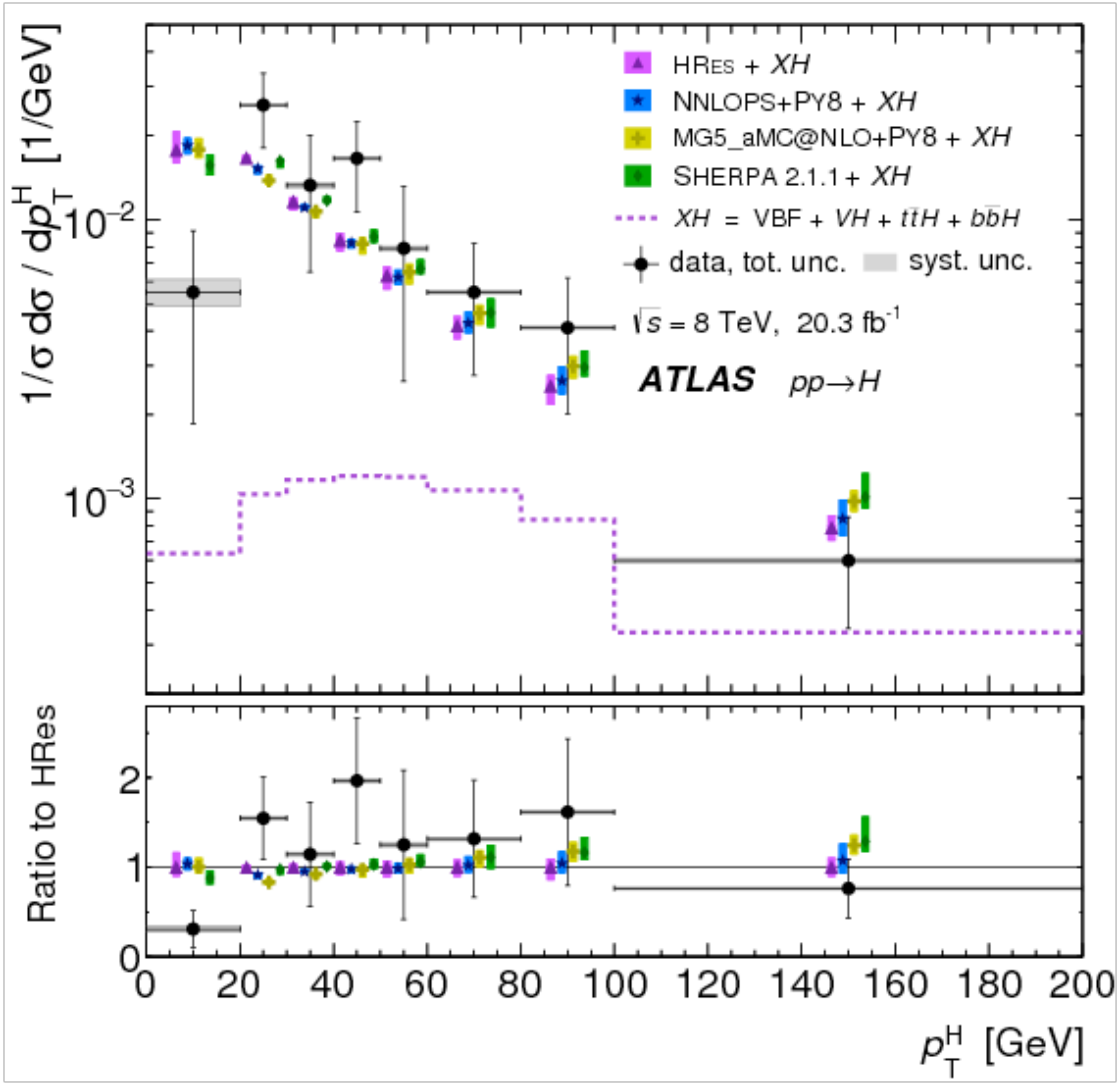
Neill, Rothstein, Vaidya, arXiv:1503.00005





NNLL+NNLO has 10-20% uncertainty, plus an unknown nonperturbative contribution

Current data



Current pT resolution of Higgs too low at low pT, will eventually be around 5 GeV

Quarkonium production

C-even (pseudo-)scalar quarkonium production promising for studying $h_1^{\perp g}$

Using the CS model and LO NRQCD we obtain:

$$\frac{d\sigma(\eta_Q)}{dy\, d^2\boldsymbol{q}_T} = \frac{2}{9}\frac{\pi^3\alpha_s^2}{M^3\, s}\,\langle 0|\mathcal{O}_1^{\eta_Q}({}^1S_0)|0\rangle\,\mathcal{C}\left[f_1^g\, f_1^g\right]\,\left[1 - R(\boldsymbol{q}_T^2)\right]$$

$$\frac{d\sigma(\chi_{Q0})}{dy\, d^2\boldsymbol{q}_T} = \frac{8}{3}\frac{\pi^3\alpha_s^2}{M^5\, s}\,\langle 0|\mathcal{O}_1^{\chi_{Q0}}({}^3P_0)|0\rangle\,\mathcal{C}\left[f_1^g\, f_1^g\right]\,\left[1 + R(\boldsymbol{q}_T^2)\right]$$

$$\frac{d\sigma(\chi_{Q2})}{dy\, d^2\boldsymbol{q}_T} = \frac{32}{9}\frac{\pi^3\alpha_s^2}{M^5\, s}\,\langle 0|\mathcal{O}_1^{\chi_{Q2}}({}^3P_2)|0\rangle\,\mathcal{C}\left[f_1^g\, f_1^g\right]$$

D.B., Pisano, PRD 86 (2012) 094007

These are color singlet model expressions, which at least may be justified for C=+ bottomonium states

Bodwin, Braaten, Lepage, 1995; Hägler, Kirschner, Schäfer, Teryaev, 2001; Maltoni, Polosa, 2004; Bodwin, Braaten, Lee, 2005; …

Bottomonium production

To extract $R(Q_T)$ one can consider 3 bottomonia and ratios of ratios:

$$\frac{\sigma(\chi_{b0})}{\sigma(\eta_b)} \frac{d\sigma(\eta_b)/d^2\boldsymbol{q}_T}{d\sigma(\chi_{b0})/d^2\boldsymbol{q}_T} \approx \frac{1+R(\boldsymbol{q}_T^2)}{1-R(\boldsymbol{q}_T^2)}$$

$$\frac{\sigma(\chi_{b0})}{\sigma(\chi_{b2})} \frac{d\sigma(\chi_{b2})/d^2\boldsymbol{q}_T}{d\sigma(\chi_{b0})/d^2\boldsymbol{q}_T} \approx 1+R(\boldsymbol{q}_T^2)$$

Uncertainties about the hadronic wave function (approximately) cancel

Very small scale differences: $m_{\eta_b} \approx m_{\chi_{b0}} \approx m_{\chi_{b2}}$

Therefore, hardly any TMD evolution effects

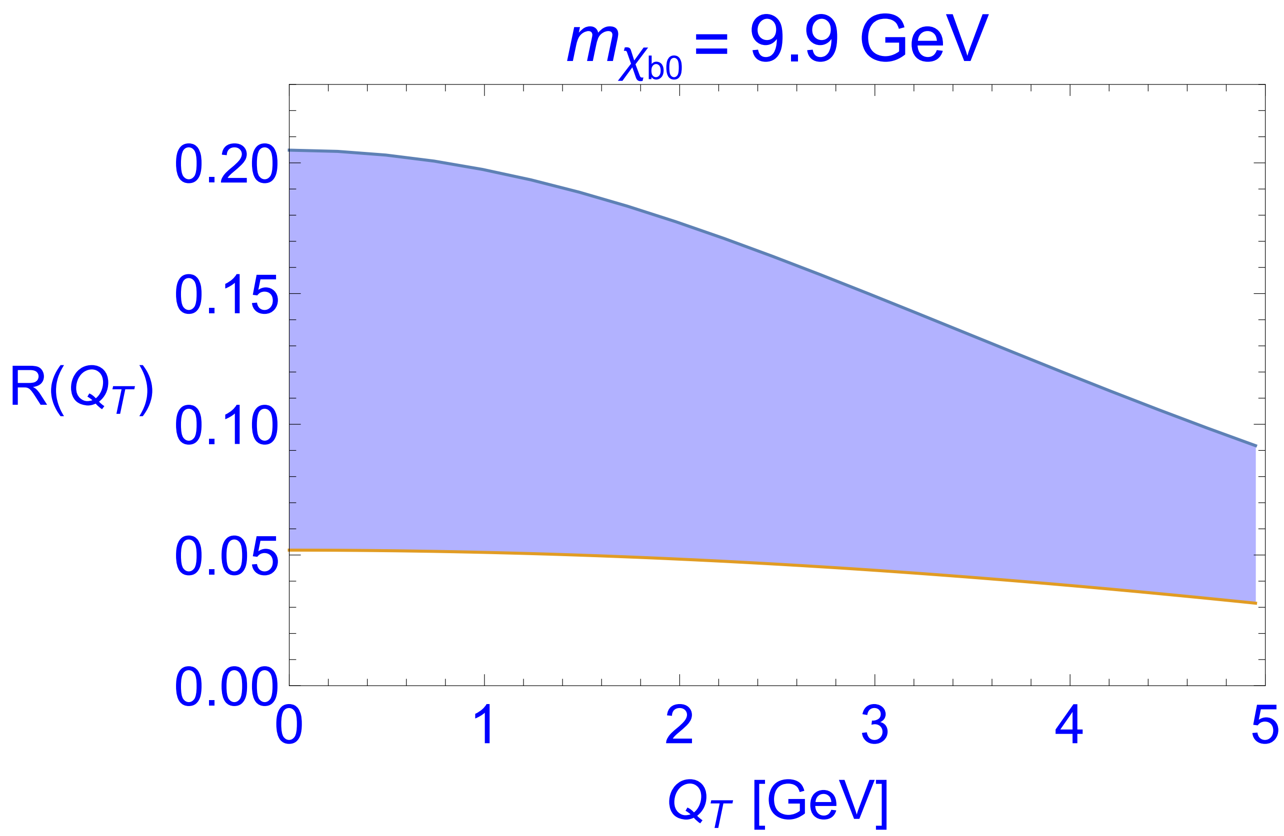
TMD factorization for the p-wave states χ_{bJ} has been called into question, but can be tested with these ratios as well

J.P. Ma, Wang, Zhao, 2014

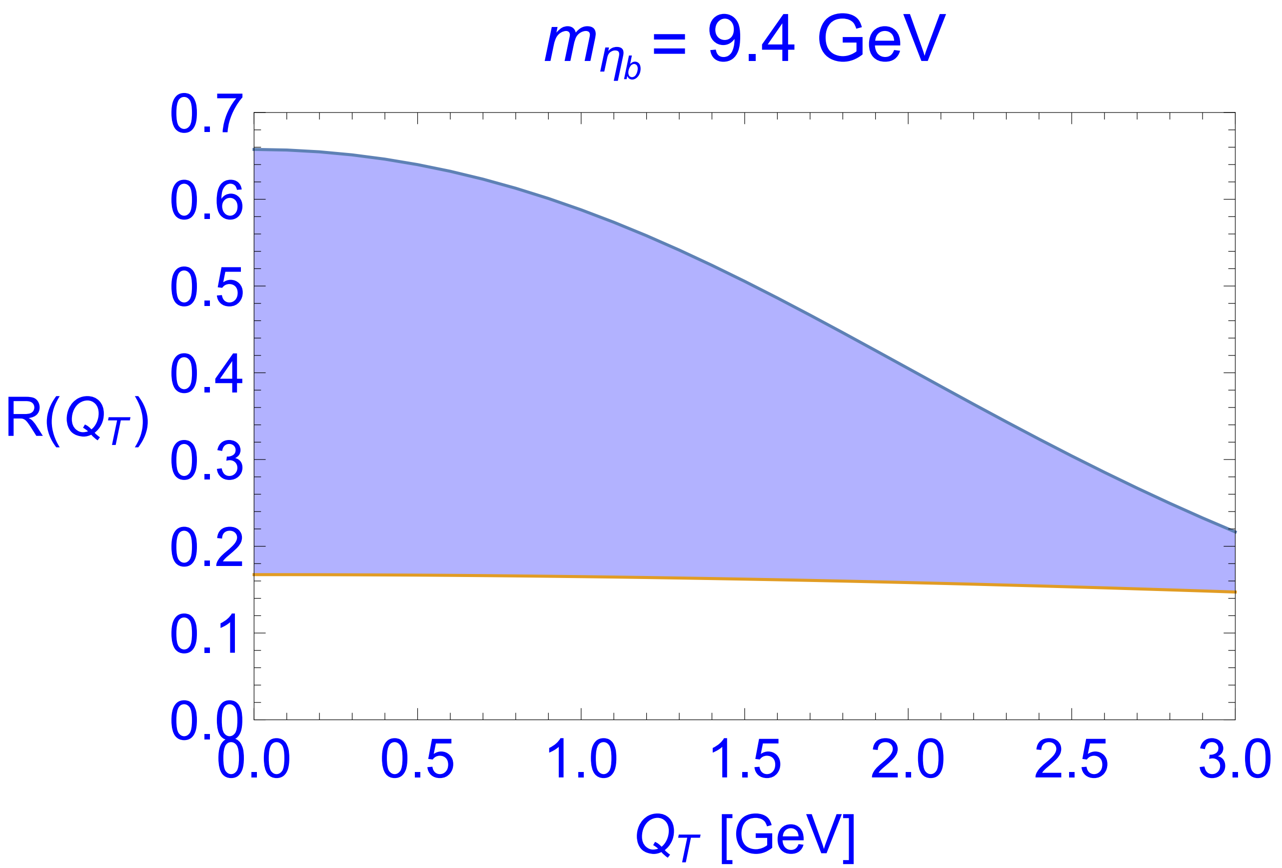
Of course, not easy experimentally, but sizeable effects are expected

Bottomonium production

The range of predictions for C-even bottomonium production:



Boer & den Dunnen, 2014



Echevarria, Kasemets, Mulders, Pisano, 2015

Conclusion: very large theoretical uncertainties in quarkonium production (more sensitive to unknown nonperturbative part than Higgs production), but larger effects

Linear gluon polarization at small x

There is no theoretical reason why $h_1^{\perp g}$ effects should be small, especially at small x

Evolution: $h_1^{\perp g}$ has the same 1/x growth as f_1

$$\tilde{h}_1^{\perp g}(x, b^2; \mu_b^2, \mu_b) = \frac{\alpha_s(\mu_b) C_A}{2\pi} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1 \right) f_{g/P}(\hat{x}; \mu_b) + \mathcal{O}(\alpha_s^2)$$

The small-x limit of the DP correlator in the TMD formalism:

$$\Gamma^{[+,-]\,ij}(x, \boldsymbol{k}_T) \xrightarrow{x \to 0} \frac{k_T^i k_T^j}{2\pi L} \Gamma_0^{[\Box]}(\boldsymbol{k}_T) \qquad U^{[\Box]} = U^{[+]}_{[0,y]} U^{[-]}_{[y,0]}$$

$$\Gamma_U^{ij}(x, \boldsymbol{k}_T) = \frac{x}{2} \left[-g_T^{ij} f_1(x, \boldsymbol{k}_T^2) + \frac{k_T^{ij}}{M^2} h_1^{\perp}(x, \boldsymbol{k}_T^2) \right] \xrightarrow{x \to 0} \frac{k_T^i k_T^j}{2M^2} e(\boldsymbol{k}_T^2)$$

$$\lim_{x \to 0} x f_1(x, \boldsymbol{k}_T^2) = \frac{\boldsymbol{k}_T^2}{2M^2} \lim_{x \to 0} x h_1^{\perp}(x, \boldsymbol{k}_T^2) = \frac{\boldsymbol{k}_T^2}{2M^2} e(\boldsymbol{k}_T^2)$$

The DP $h_1^{\perp g}$ becomes maximal when x → 0

D.B., Cotogno, van Daal, Mulders, Signori, Zhou, 2016

→ *talk by Piet Mulders*

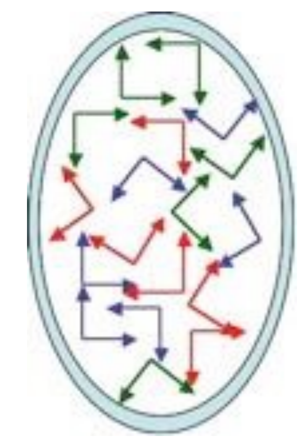
Polarization of the CGC

CGC framework calculations show the CGC gluons are in fact linearly polarized

$$h_{1,WW}^{\perp g} \ll f_{1,WW}^{\perp g} \quad \text{for } k_\perp \ll Q_s, \qquad h_{1,WW}^{\perp g} = 2 f_{1,WW}^{\perp g} \quad \text{for } k_\perp \gg Q_s$$

$$x h_{1,DP}^{\perp g}(x, k_\perp) = 2x f_{1,DP}^{g}(x, k_\perp)$$

Metz, Zhou '11



The WW $h_1^{\perp g}$ is (moderately) suppressed for small transverse momenta:

$$\frac{h_{1\,WW}^{\perp\,g}}{f_{1\,WW}} \propto \frac{1}{\ln Q_s^2/k_\perp^2}$$

The CGC can be 100% polarized, but its observable effects depend on the process

The "k_T-factorization" approach (CCFM) yields maximum polarization too:

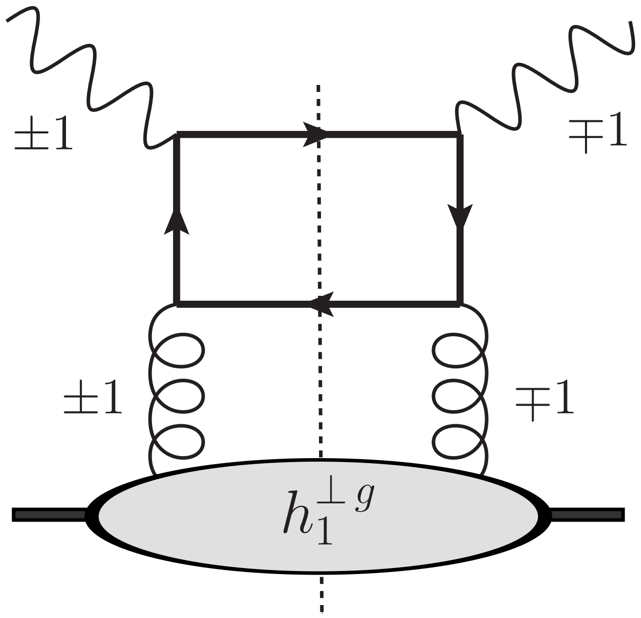
$$\Gamma_g^{\mu\nu}(x, \boldsymbol{p}_T)_{\text{max pol}} = \frac{p_T^\mu p_T^\nu}{\boldsymbol{p}_T^2} \, x \, f_1^g$$

Catani, Ciafaloni, Hautmann, 1991

Heavy quark production

$h_1^{\perp g}$ can be probed in open charm and bottom quark pair production in DIS
Here it appears only once, so less suppressed

$$ep \to e' Q\bar{Q} X$$



It leads to a cos $2(\phi_T - \phi_\perp)$ modulation in heavy quark pair production in DIS
$\phi_{T/\perp}$: angles of $K_\perp^Q \pm K_\perp^{\bar{Q}}$

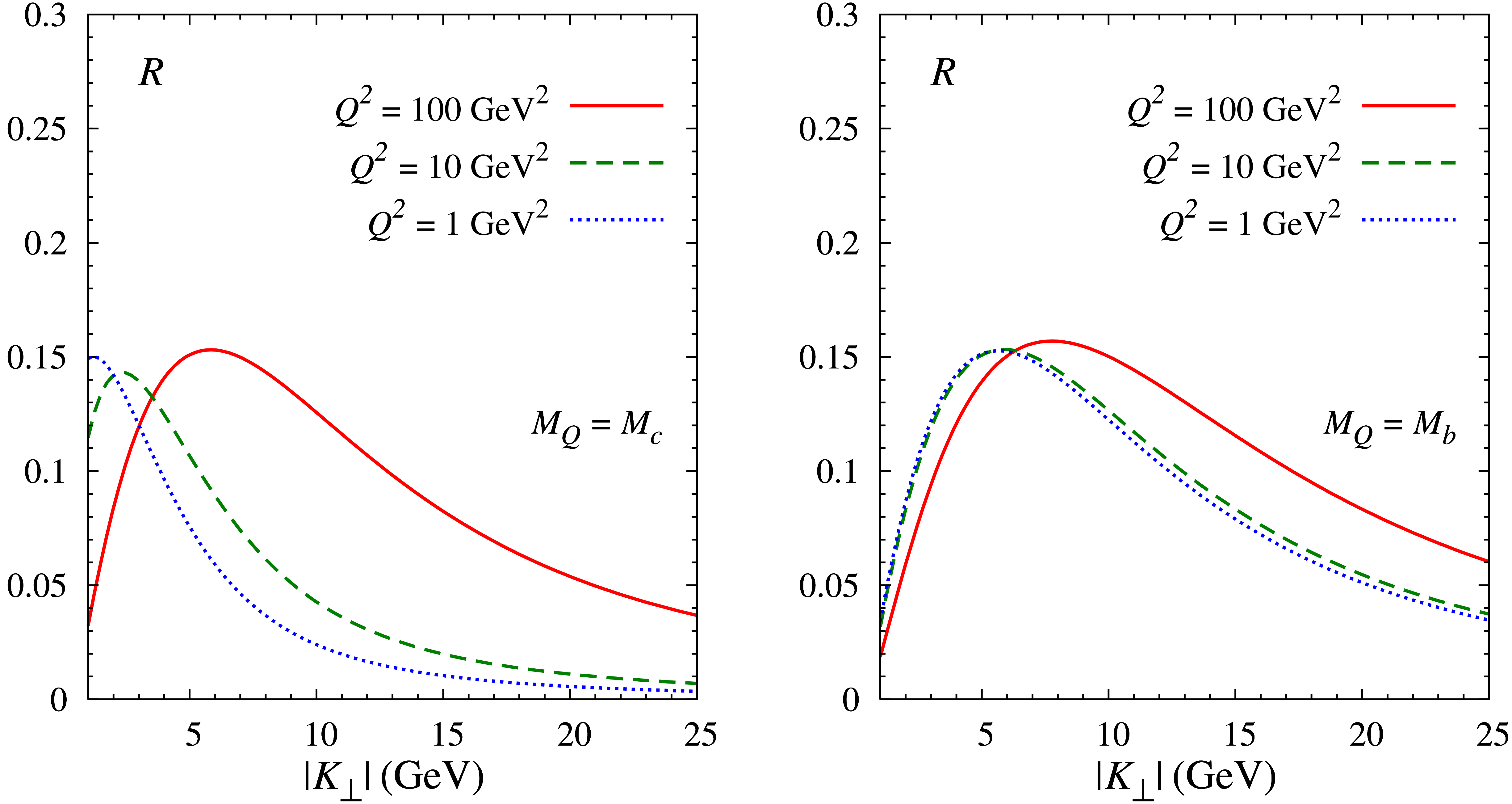
D.B., Brodsky, Mulders & Pisano, 2010

Best measured at an Electron-Ion Collider (USA) or LHeC (CERN)

HL-LHeC would be a Higgs factory (~40k Higgs events per year)
EIC will have the advantage of polarized protons

Maximum asymmetries in heavy quark production

$ep \to e'Q\bar{Q}X$ $\qquad$ $R = \text{bound on } |\langle \cos 2(\phi_T - \phi_\perp)\rangle|$



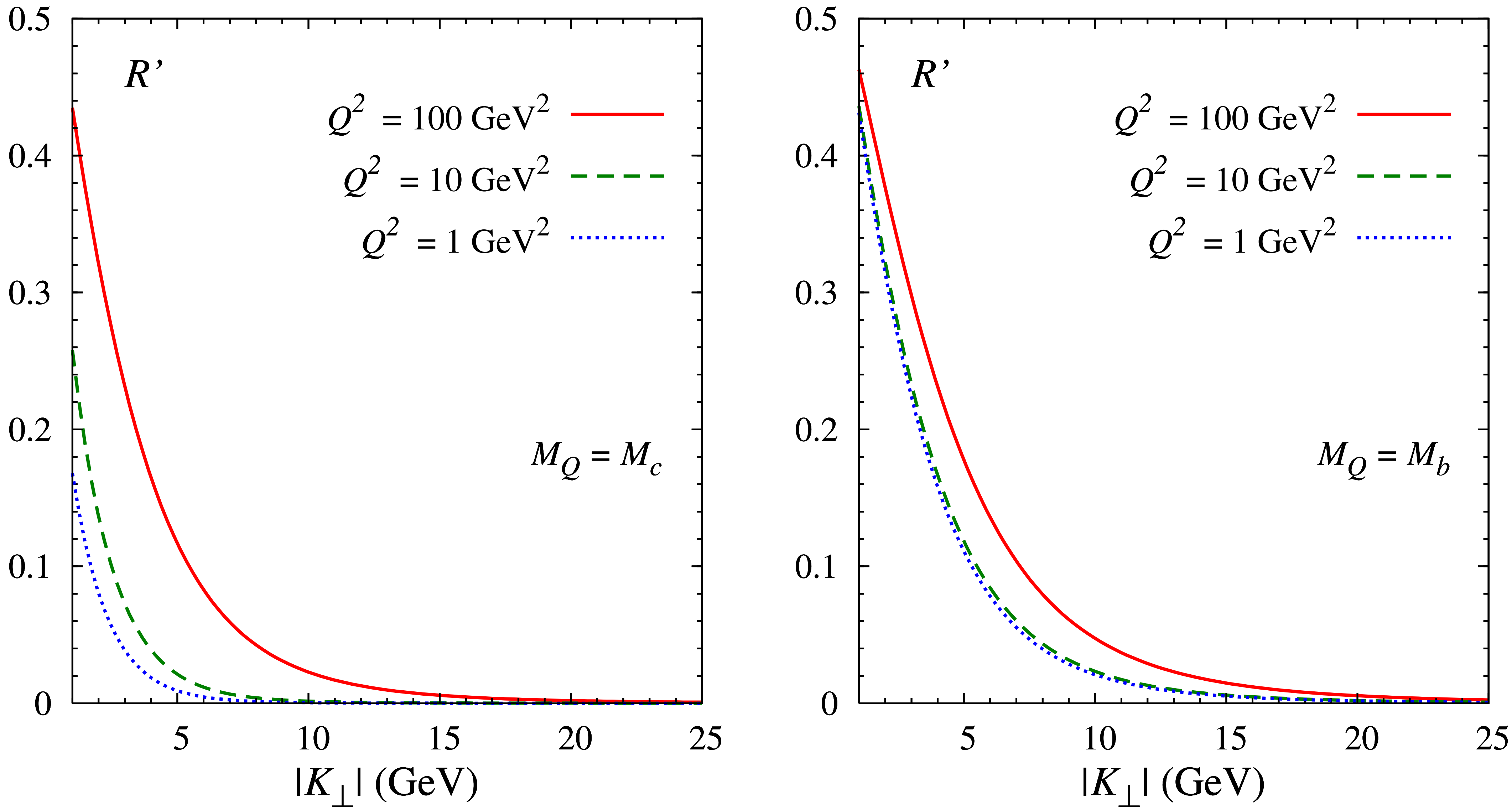
$y = 0.01$

Pisano, D.B., Brodsky, Buffing & Mulders, JHEP 10 (2013) 024

Maximum asymmetries in heavy quark production

There are also angular asymmetries w.r.t. the lepton scattering plane, which are mostly relevant at smaller $|K_\perp|$

$$ep \to e' Q \bar{Q} X \qquad R' = \text{bound on } |\langle \cos 2(\phi_\ell - \phi_T) \rangle|$$

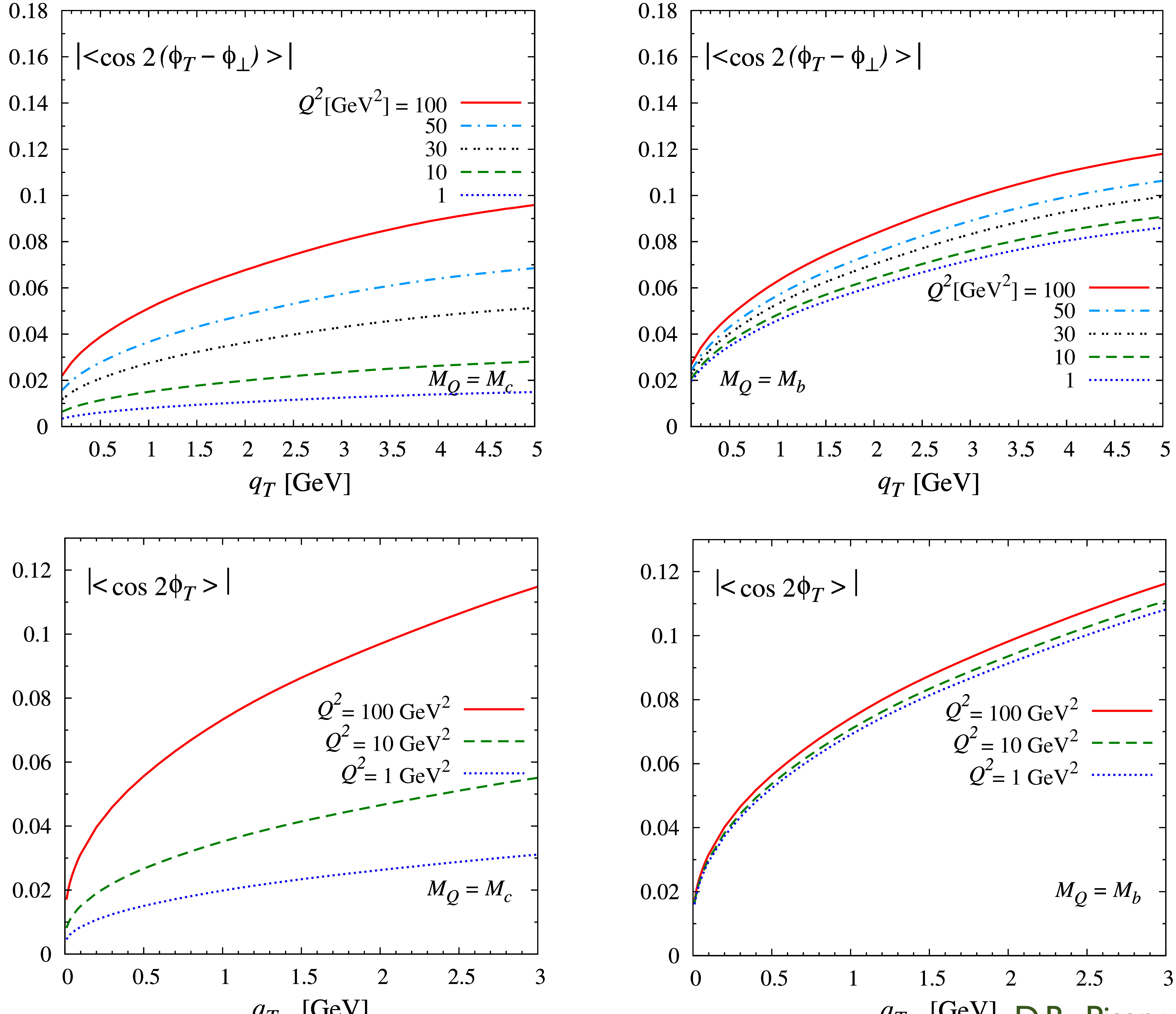


$y = 0.01$

[Pisano, D.B., Brodsky, Buffing & Mulders, 2013]

Heavy quark pair production at EIC

MV model



$|\boldsymbol{K}_\perp| = 10\,\text{GeV}$

$z = 0.5$

$y = 0.3$

$|\boldsymbol{K}_\perp| = 6\,\text{GeV}$

$z = 0.5$

$y = 0.1$

D.B., Pisano, Mulders, Zhou, 2016

Dijet production at EIC

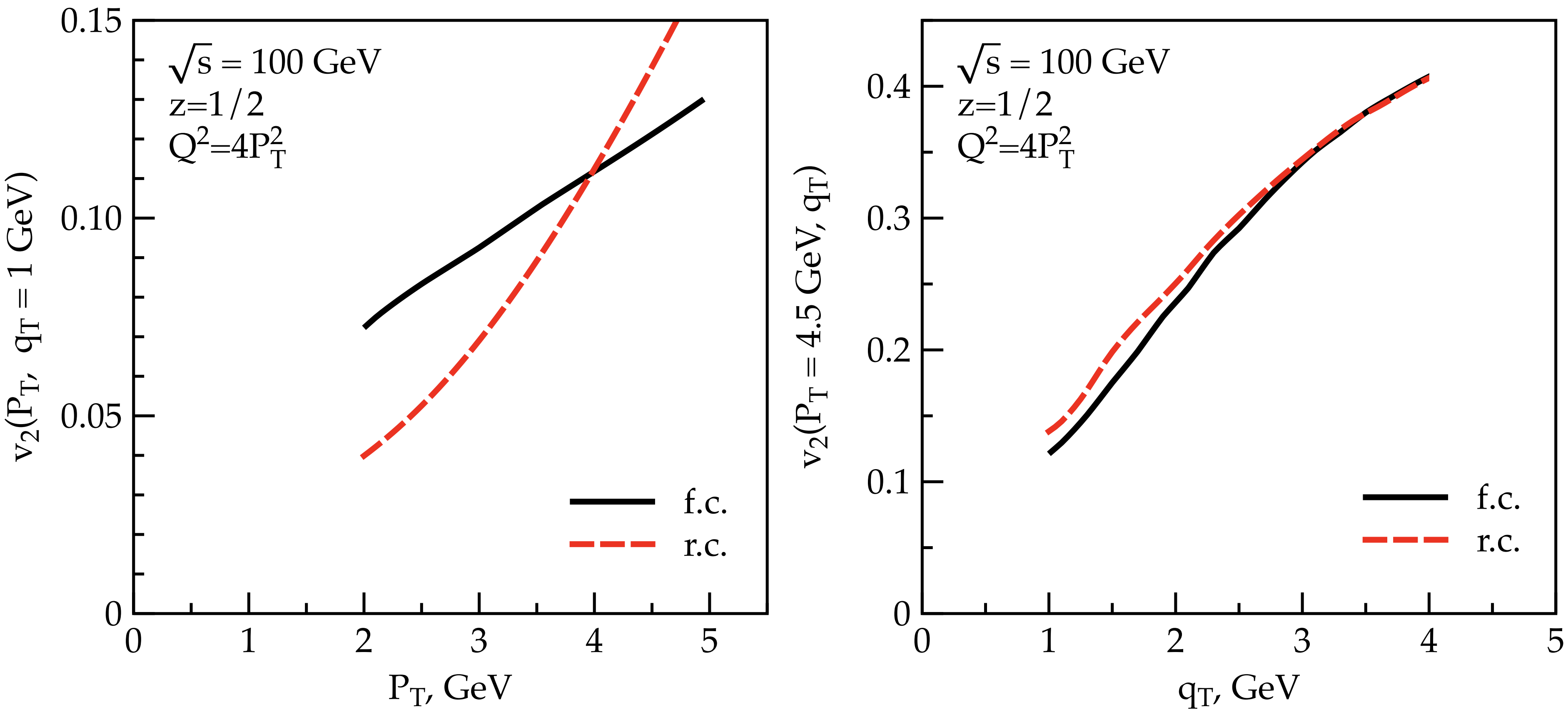
WW $h_1^{\perp g}$ accessible in dijet production in eA collisions at a high-energy EIC
[Metz, Zhou 2011; Pisano, D.B., Brodsky, Buffing, Mulders, 2013; D.B., Pisano, Mulders, Zhou, 2016]

The WW $h_1^{\perp g}$ is (moderately) suppressed for small transverse momenta:

$$\frac{h_{1\,WW}^{\perp\,g}}{f_{1\,WW}} \propto \frac{1}{\ln Q_s^2/k_\perp^2}$$

Metz, Zhou '11

Polarization shows itself through a cos2ϕ distribution



Large effects are found
Dumitru, Lappi, Skokov, 2015

$y = 1$

Gluon Sivers effect at small x

Small gluon Sivers effect?

Arguments suggesting gluon Sivers is small:

- Burkardt sum rule already (approximately) satisfied by up and down quarks

$$\sum_{a=q,g} \int f_{1T}^{\perp(1)a}(x)\, dx = 0$$

- small Sivers asymmetry on deuteron target as found by COMPASS
[Brodsky & Gardner, 2006]

- $1/N_c$ suppressed at not too small x ($x \sim 1/N_c$), of order of the flavor singlet u+d
[Efremov, Goeke, Menzel, Metz, Schweitzer, 2005]

- small A_N at midrapidity (small gluon Sivers function in the GPM)
[Anselmino, D'Alesio, Melis & Murgia, 2006; D'Alesio, Murgia, Pisano, 2015]

Note however that A_N in pion production is not a TMD factorizing process
COMPASS high-pT hadron pairs and other constraints are about fairly large x

Gluon Sivers function is constrained to be $\lesssim$ 30% of nonsinglet quark Sivers function
This is of natural size and will lead to smaller asymmetries, but not necessarily tiny

D.B., Lorcé, Pisano & Zhou, 2015

Gluon Sivers effect at small x

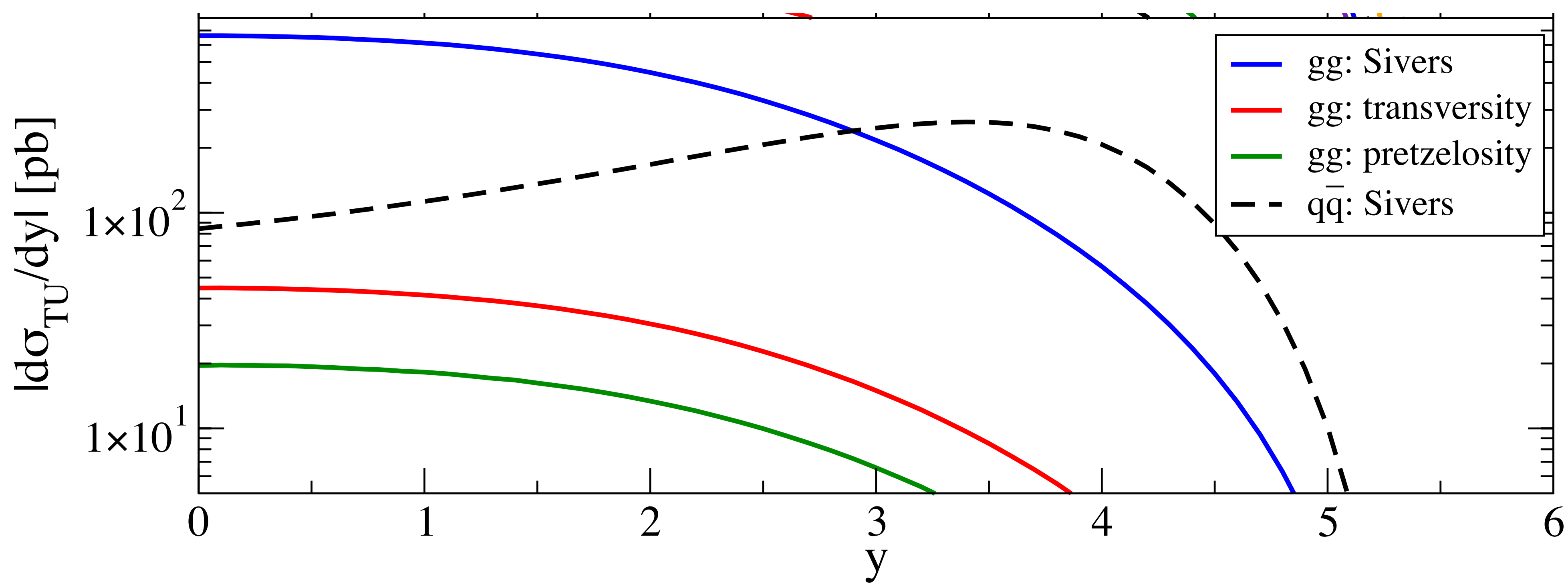
Selection of processes that probe the WW (f type) or DP (d type) Sivers gluon TMD:

	DY	SIDIS	$p^\uparrow A \to h\, X$	$p^\uparrow A \to \gamma^{(*)}\,\mathrm{jet}\, X$	$p^\uparrow p \to \gamma\,\gamma\, X$ $p^\uparrow p \to J/\psi\,\gamma\, X$ $p^\uparrow p \to J/\psi\, J/\psi\, X$	$e\, p^\uparrow \to e'\, Q\, \overline{Q}\, X$ $e\, p^\uparrow \to e'\, j_1\, j_2\, X$
$f_{1T}^{\perp\, g\, [+,+]}$ (WW)	$\times$	$\times$	$\times$	$\times$	$\surd$	$\surd$
$f_{1T}^{\perp\, g\, [+,-]}$ (DP)	$\surd$	$\surd$	$\surd$	$\surd$	$\times$	$\times$

backward hadron production

[Qiu, Schlegel, Vogelsang, 2011]

$p^\uparrow p \to \gamma\gamma X$



$\sqrt{s}$=500 GeV, $p_T^\gamma \geq 1$ GeV, integrated over $4 < Q^2 < 30$ GeV^2, $0 \leq q_T \leq 1$ GeV

At photon pair rapidity y < 3 gluon Sivers dominates and max($d\sigma_{TU}/d\sigma_{UU}$) ~ 30-50%

Gluon Sivers effect at small x

At small x the large k_T tail of the WW Sivers function is suppressed by a factor of x compared to the unpolarized gluon function

The DP-type Sivers function is not suppressed and can be probed in pA collisions

$$\Gamma^{[+,-]\,ij}(x,\boldsymbol{k}_T) \xrightarrow{x\to 0} \frac{k_T^i k_T^j}{2\pi L}\Gamma_0^{[\Box]}(\boldsymbol{k}_T)$$

The DP-type Sivers function at small x turns out to be the ***spin-dependent odderon***

$$\Gamma_{(d)}^{(T-\text{odd})} \equiv \left(\Gamma^{[+,-]} - \Gamma^{[-,+]}\right) \propto \text{F.T.}\,\langle P, S_T|\text{Tr}\left[U^{[\Box]}(0_T, y_T) - U^{[\Box]\dagger}(0_T, y_T)\right]|P, S_T\rangle$$

D.B., Echevarria, Mulders, Zhou, 2016

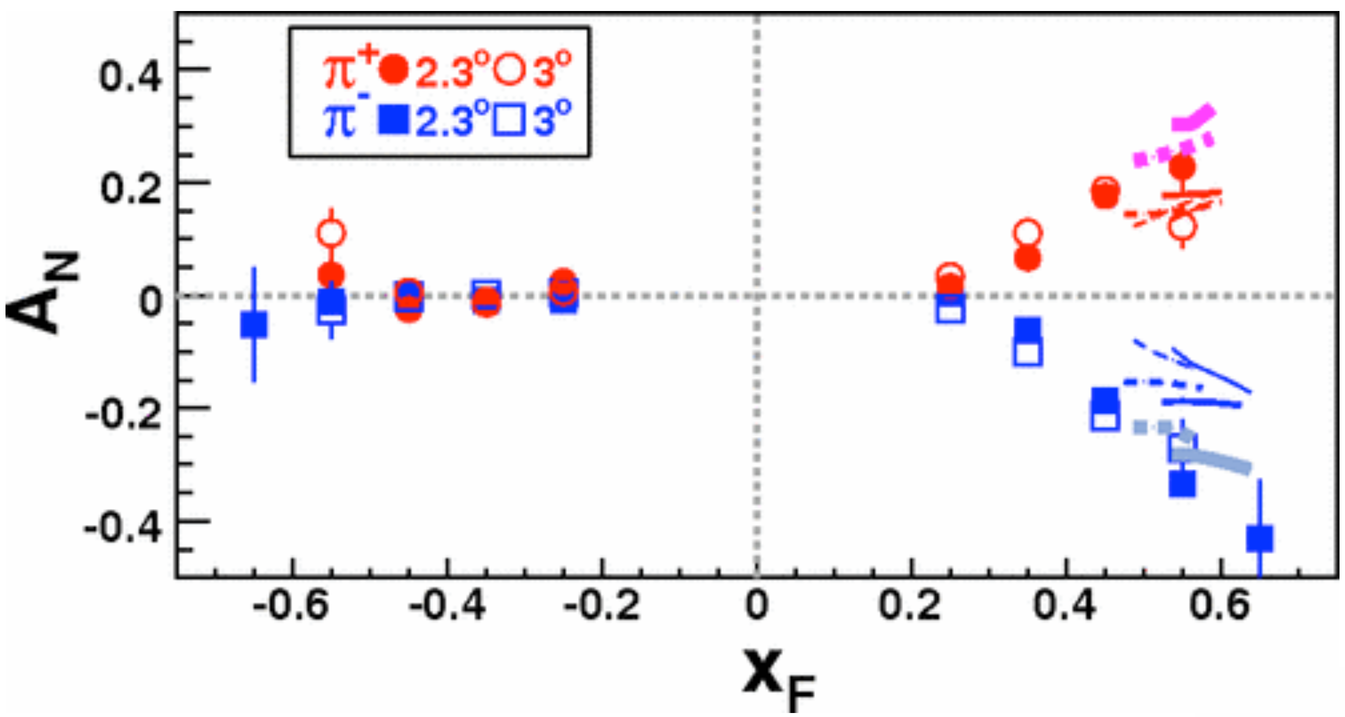
a single Wilson loop matrix element

$$U^{[\Box]} = U^{[+]}_{[0,y]} U^{[-]}_{[y,0]}$$

It is the only relevant contribution in A_N at negative x_F, as opposed to the many contributions at positive x_F

The imaginary part of the Wilson loop determines the gluonic single spin asymmetry

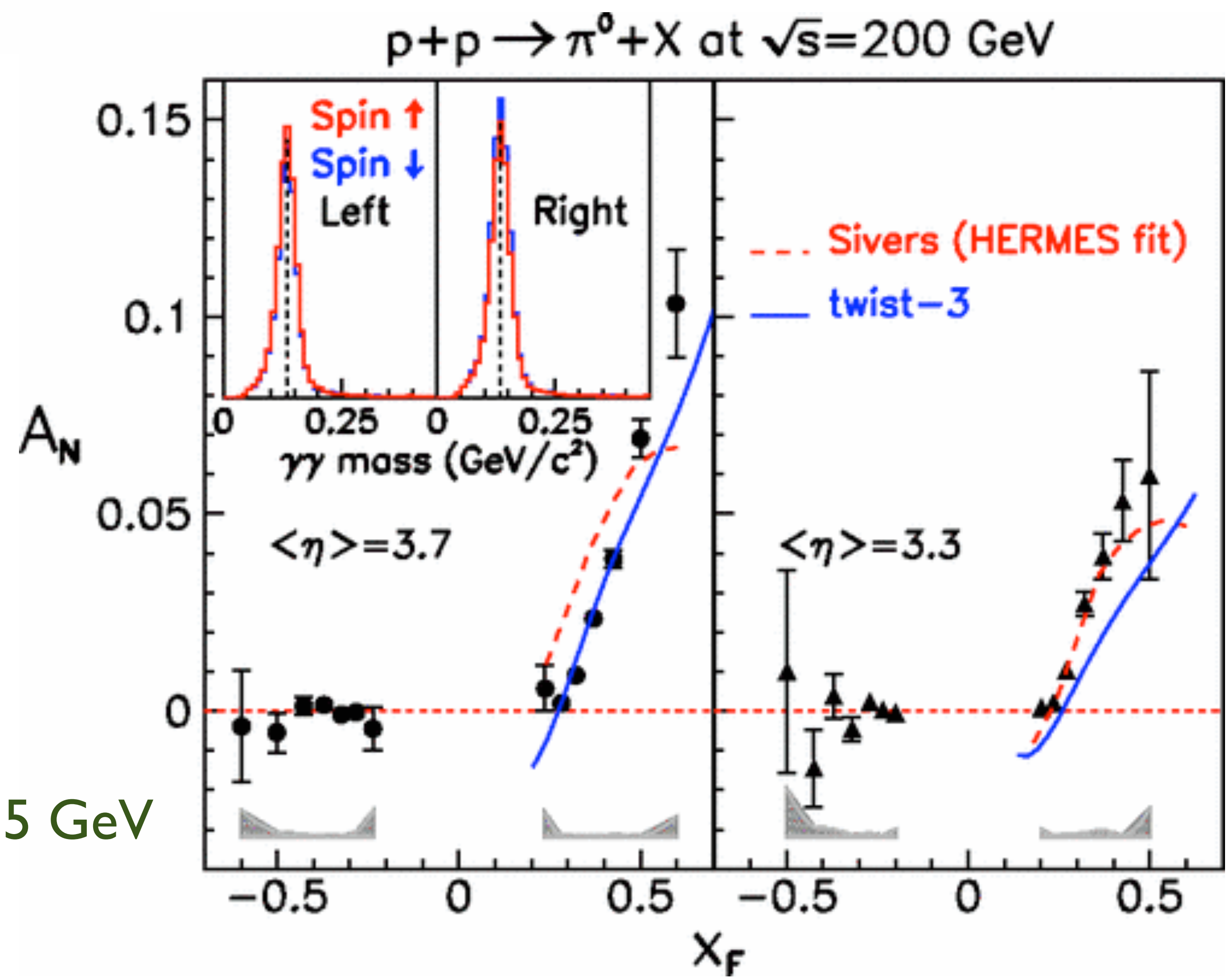
$p^{\uparrow}p \rightarrow h^{\pm} X$ at $x_F < 0$



BRAHMS, 2008 $\sqrt{s}$ = 62.4 GeV
low p_T, up to roughly 1.2 GeV
where gg channel dominates

spin-dependent odderon is C-odd,
whereas gg in the CS state is C-even

expect smaller asymmetries
in neutral pion and jet production



STAR, 2008
$\sqrt{s}$ = 200 GeV
p_T between 1 and 3.5 GeV

Conclusions

Conclusions

- All TMDs are process dependent, with observable and testable effects
- At small x the unpolarized WW and DP gluon TMDs both matter and there are sufficient processes in ep and pp collisions to test the expectations
- Same applies to the linear polarization of gluons inside unpolarized hadrons:
  In pp collisions percent level effects, except in quarkonium production
  In ep collisions it could be much larger (10% or more) & its sign can be determined
- The CGC can be maximally polarized, although not all processes will be (fully) sensitive to it
- Two distinct gluon Sivers TMDs can be measured in $p^{\uparrow}p$ and $p^{\uparrow}A$ collisions (RHIC & AFTER@LHC), the WW-type allows for a sign-change test w.r.t. $ep^{\uparrow}$ (EIC)
- As $x \to 0$ only the DP gluon Sivers TMD remains, which then corresponds to the spin-dependent odderon, a T-odd and C-odd single Wilson loop matrix element that determines A_N at negative x_F

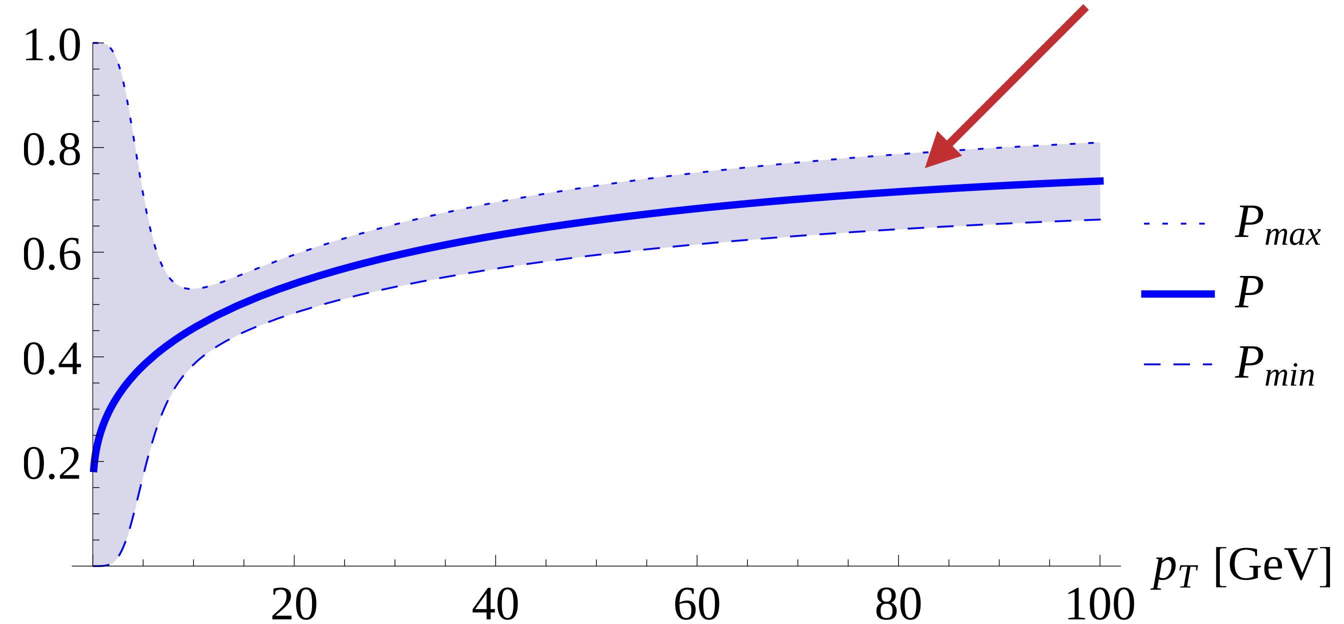
Back-up slides

Size of the effect

$$\frac{\alpha_s P' \otimes f_1}{\alpha_s P \otimes f_1}$$

Amount of linear gluon polarization:

D.B., Den Dunnen, Pisano, Schlegel '13



Ratio of large-k_T tails of $h_1^\perp$ and f_1 is large, does ***not*** mean large effects at large Q_T (observables involve ***integrals*** over all partonic k_T)

What matters is the small-b behavior of the Fourier transformed TMD:

$$\tilde{f}_1^g(x, b^2; \mu_b^2, \mu_b) = f_{g/P}(x; \mu_b) + \mathcal{O}(\alpha_s)$$

$$\tilde{h}_1^{\perp g}(x, b^2; \mu_b^2, \mu_b) = \frac{\alpha_s(\mu_b) C_A}{2\pi} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1 \right) f_{g/P}(\hat{x}; \mu_b) + \mathcal{O}(\alpha_s^2)$$

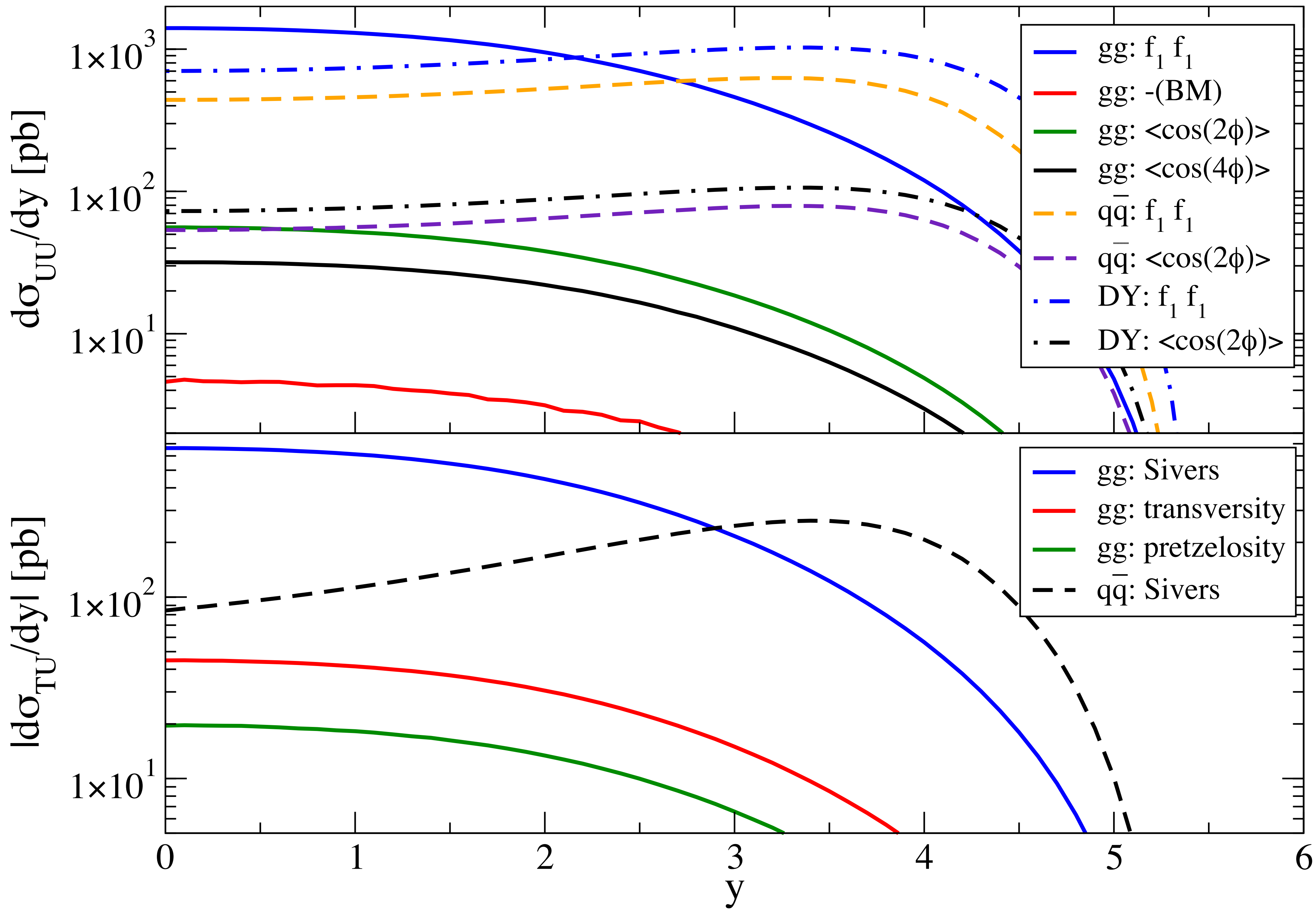
[Nadolsky, Balazs, Berger, C.-P. Yuan, 2007; Catani, Grazzini, 2010; P. Sun, B.-W. Xiao, F. Yuan, 2011]

The linear polarization starts at order α_s, leading to a **suppression** w.r.t. f_1

Photon pair production

$pp \to \gamma\gamma X$

$p^{\uparrow}p \to \gamma\gamma X$



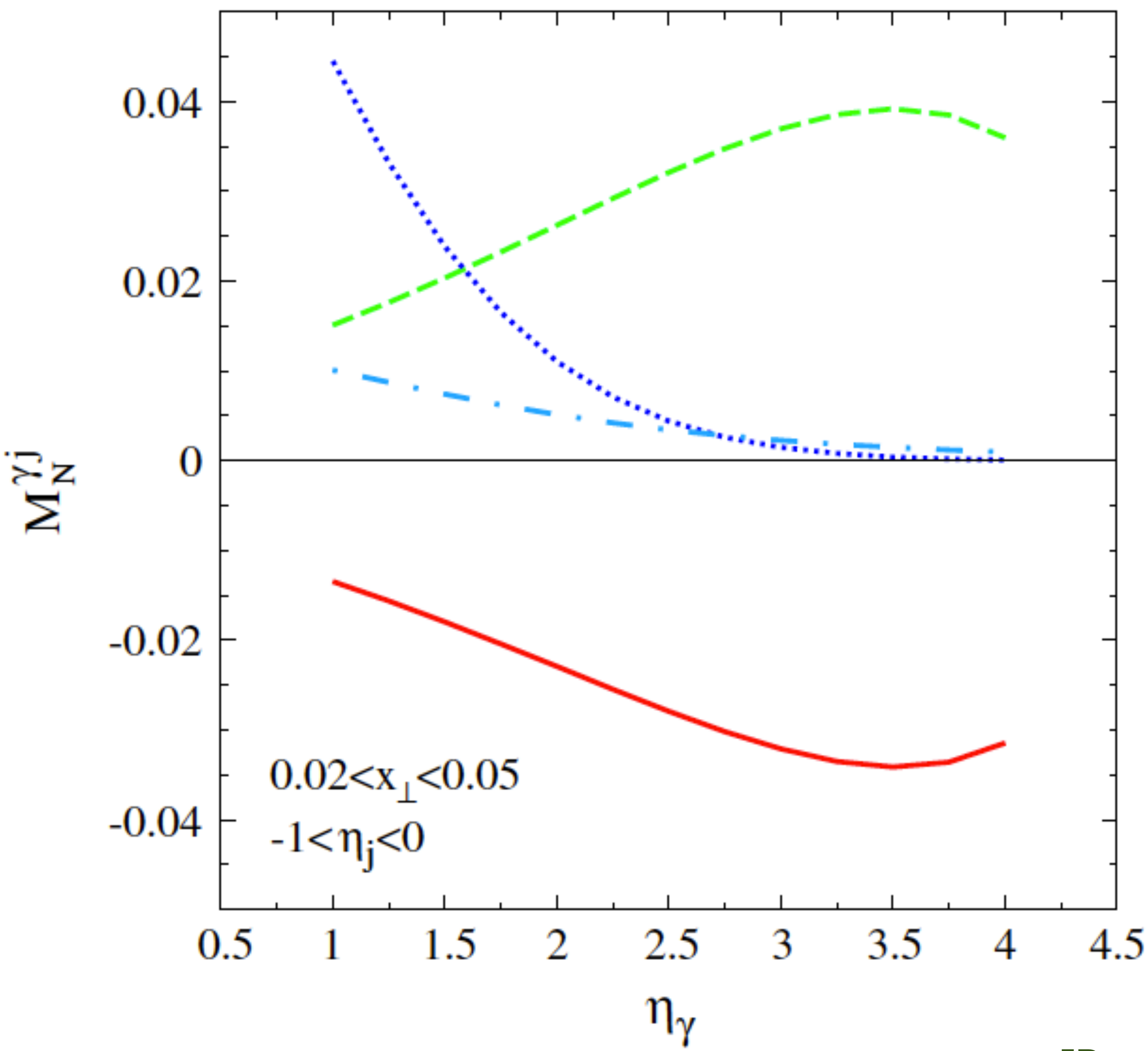
$\sqrt{s}$=500 GeV, $p_T^{\gamma} \geq 1$ GeV, integrated over $4 < Q^2 < 30$ GeV^2, $0 \leq q_T \leq 1$ GeV

At photon pair rapidity y < 3 gluon Sivers dominates and max($d\sigma_{TU}/d\sigma_{UU}$) ~ 30-50%

[Qiu, Schlegel, Vogelsang, 2011]

Photon-jet production

$$M_N^{\gamma j}(\eta_\gamma, \eta_j, x_\perp) = \frac{\int d\phi_j\, d\phi_\gamma \frac{2|\boldsymbol{K}_{\gamma\perp}|}{M} \sin(\delta\phi) \cos(\phi_\gamma) \frac{d\sigma}{d\phi_j\, d\phi_\gamma}}{\int d\phi_j\, d\phi_\gamma \frac{d\sigma}{d\phi_j\, d\phi_\gamma}}$$



Prediction for the azimuthal moment at $\sqrt{s}$=200 GeV, $p_T^\gamma \geq 1$ GeV, integrated over $-1 \lesssim \eta_j \lesssim 0$, $0.02 \lesssim x_\perp \lesssim 0.05$

Dashed line: GPM

Solid line: using gluonic-pole cross sections

Dotted line: maximum contribution from the gluon Sivers function (absolute value)

Dot-dashed line: maximum contribution from the Boer-Mulders function (abs. value)

[Bacchetta, Bomhof, D'Alesio, Mulders, Murgia, 2007]

WW vs DP

At small x the unpolarized WW and DP gluon TMDs both matter and there are sufficient processes in ep and pp collisions to test the expectations

How different can the two unpolarized gluon distributions be?

The first transverse moment must coincide

$$\int d\boldsymbol{k}_T\, f_1^{g\,[+,+]}(x,\boldsymbol{k}_T^2) \;=\; \int d\boldsymbol{k}_T\, f_1^{g\,[+,-]}(x,\boldsymbol{k}_T^2)$$

Also the large k_T tail of the functions must coincide

Therefore, the two functions can have rather different shapes and magnitudes