Gluonic Spin Orbit Correlations

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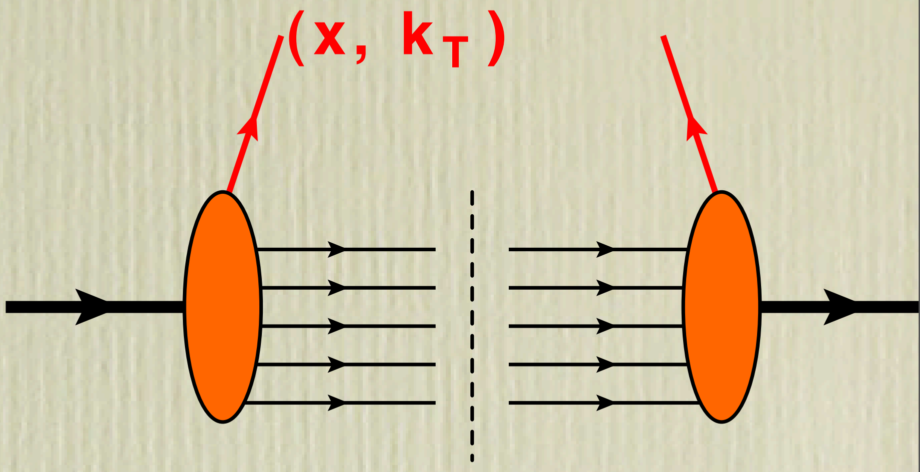
in collaboration with W. Vogelsang, J.-W. Qiu; D. Boer, C. Pisano, W. den Dunnen

"Orbital Angular Momentum in QCD"
INT, Seattle, Feb. 10, 2012

Transverse Momentum Dependent PDFs

Idea of TMDs:



Implement "intrinsic" transverse parton momentum k_T

→ different kind of factorization

→ opportunity to study different aspects of hadron spin structure (e.g. spin-orbit correlations, overlap rep. etc.)

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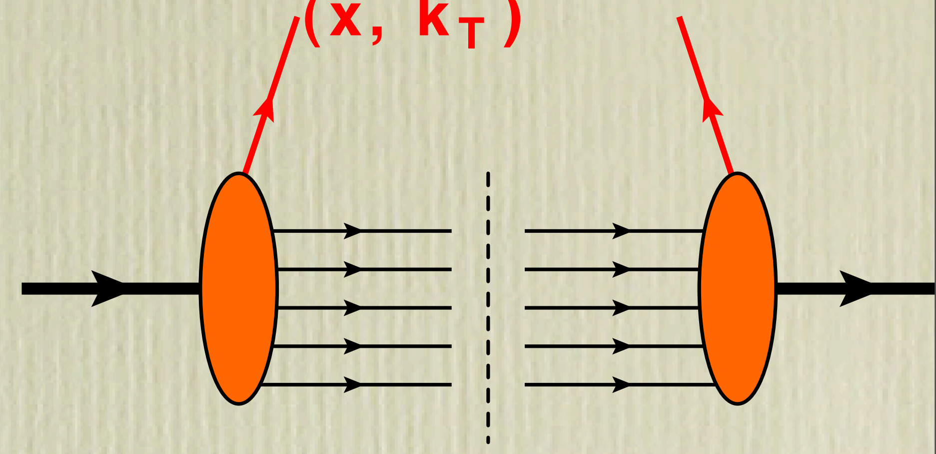

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$$\Phi_{ij}(x, \vec{k}_T; S) = \int \frac{dz^- d^2 z_T}{2(2\pi)^3}\, e^{ik\cdot z} \langle P, S|\, \bar{\psi}_j(0) \mathcal{W}_{\mathrm{SIDIS/DY}}[0, z]\, \psi_i(z)\, |P, S\rangle \Big|_{z^+=0}$$

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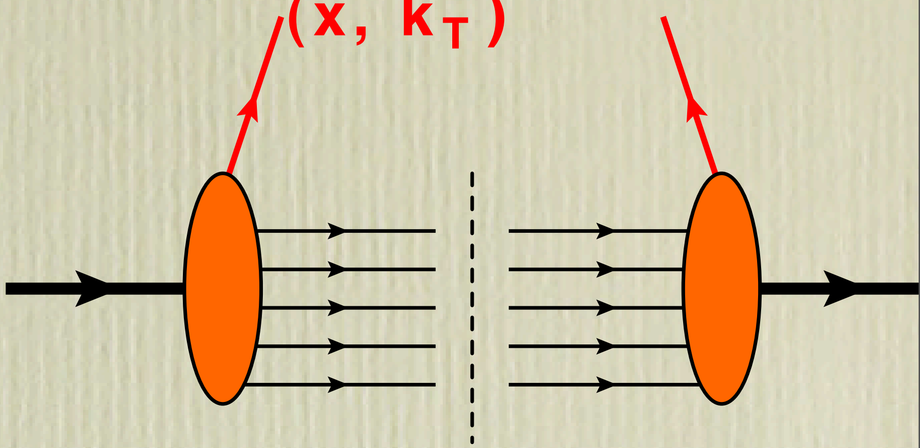

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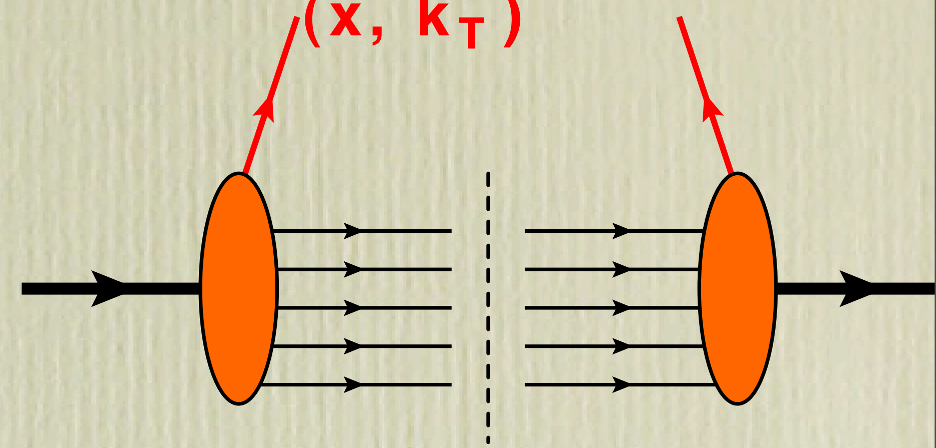

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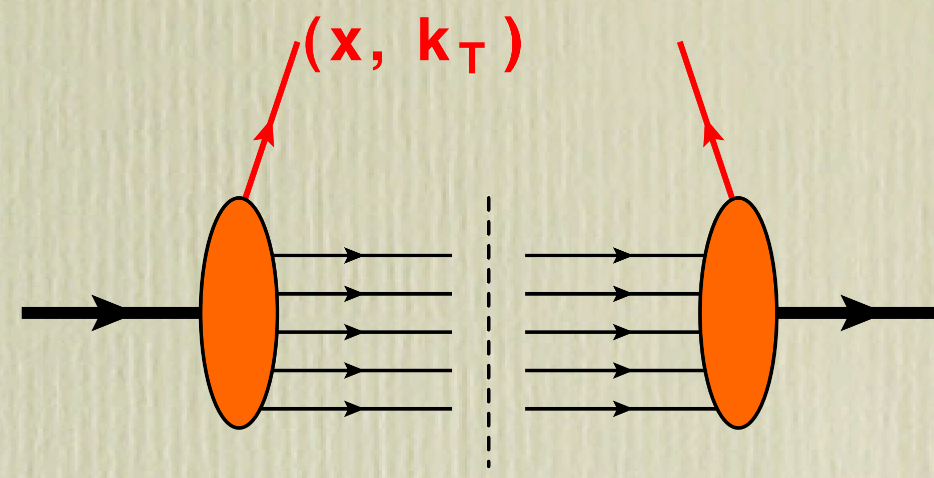

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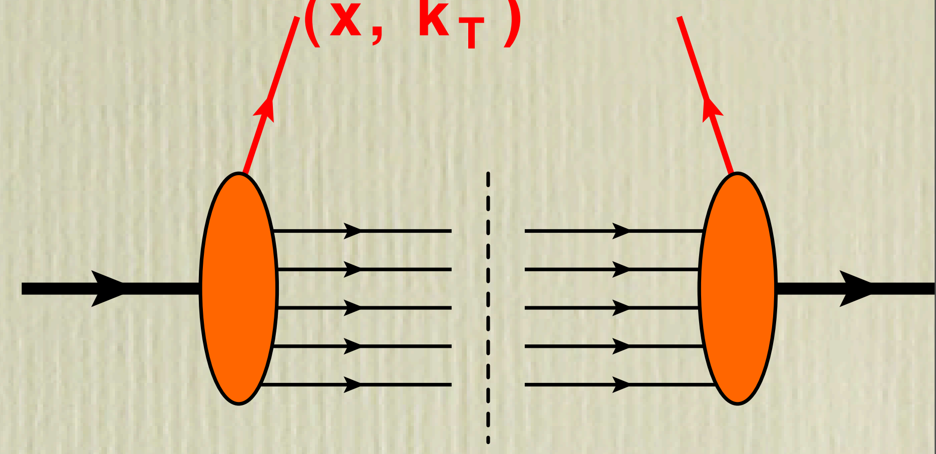

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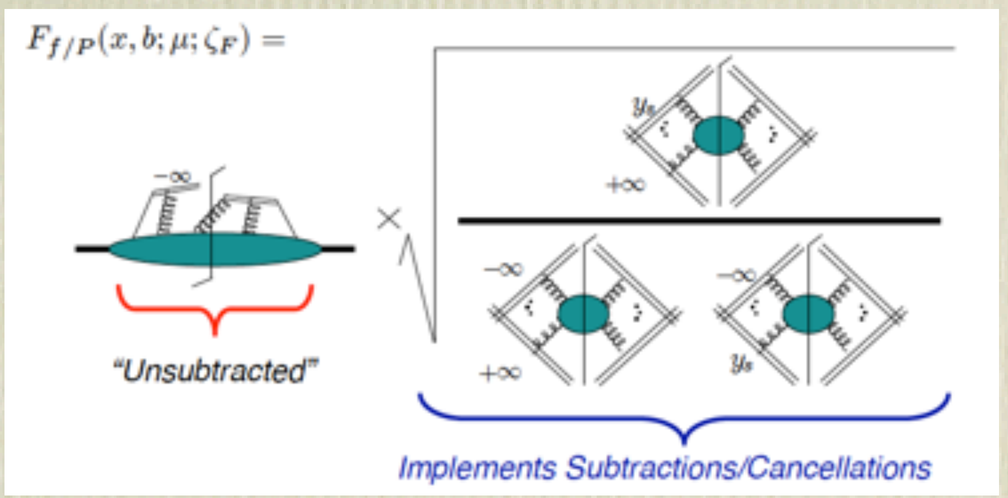
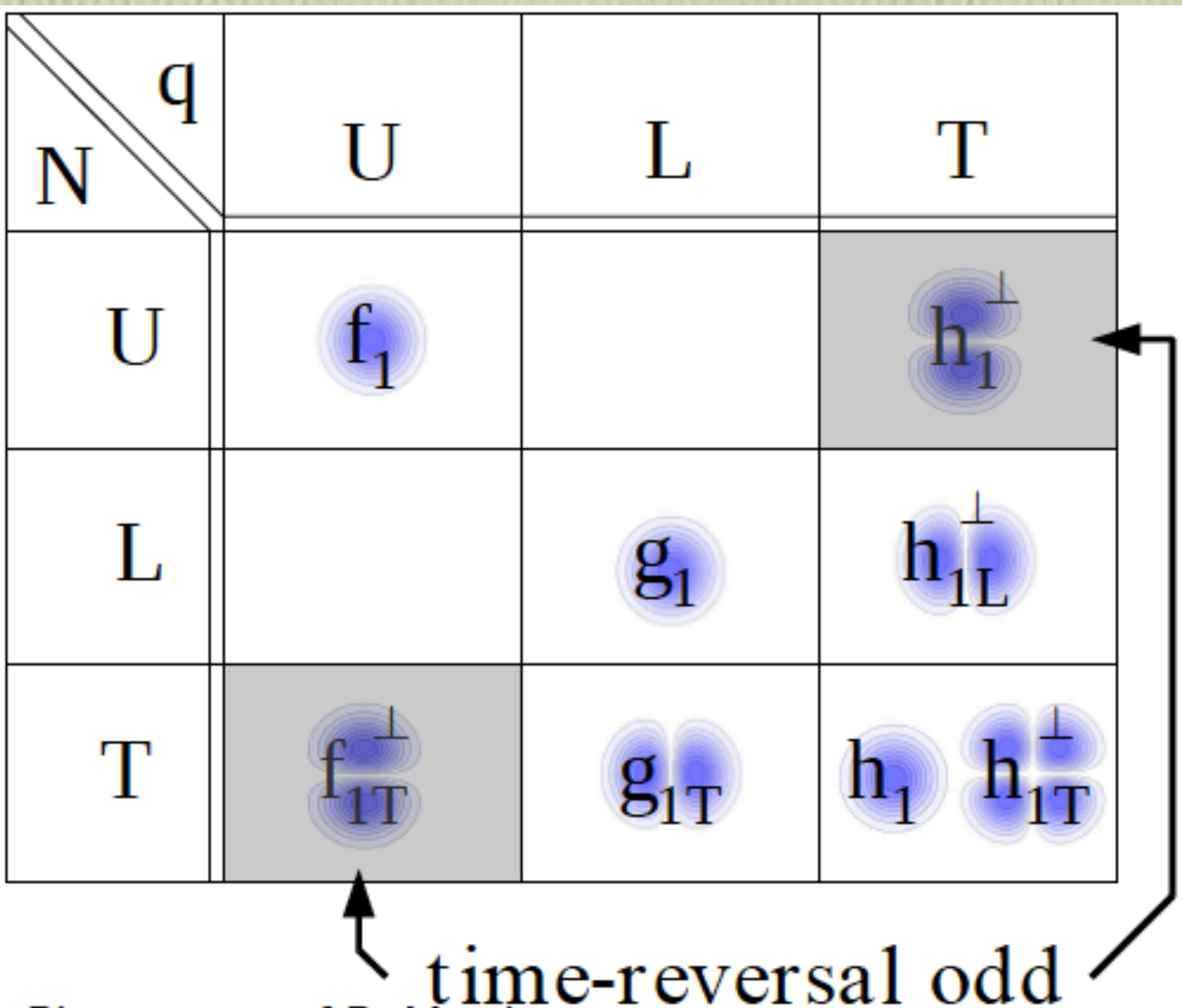
$$\Phi_{ij}(x,\vec{k}_T;S;\xi,\mu)$$

evolution equations for ξ, μ



Quark spin projection of correlator on $\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma^\perp\gamma_5$

→ 8 quark TMDs, catagorized by nucleon/quark spin



Plot courtesy of B. Musch

<u>well-studied :</u>

[experimentally & theoretically]

Sivers function

Boer-Mulders function

<u>(naive) collinear limits:</u>

unpolarized, helicity, transversity

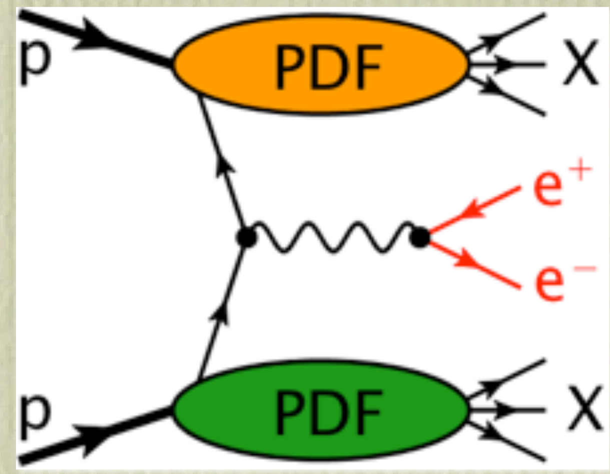
<u>“wormgear” functions</u>

<u>“pretzelosity”</u>

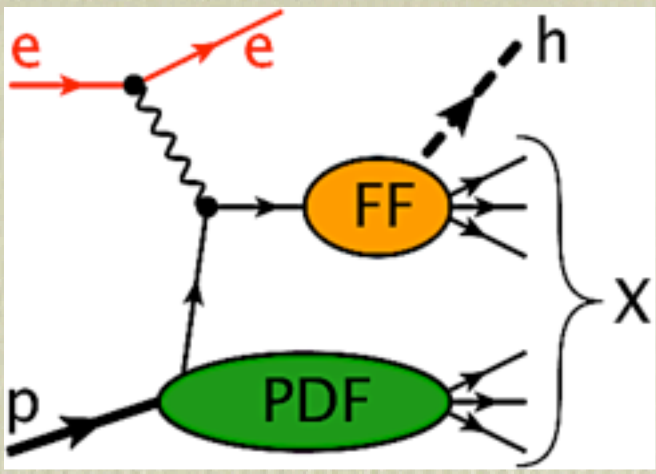
quadrupole structure

Quark TMDs in Drell-Yan & SIDIS

“intrinsic” transverse parton momentum through small final state transverse momenta



$q_T \ll Q$



$P_{hT} \ll Q$

TMD factorization

[Aybat, Rogers, PRD83, 114042; Collins’ “Foundations of pQCD”]

Drell-Yan

$$W^{\mu\nu} \sim \int d^2k_{aT} d^2k_{bT}\, \delta^{(2)}(\vec{k}_{aT} + \vec{k}_{bT} - \vec{q}_T)\, \mathrm{Tr}[\hat{M}^\mu \Phi(x_a, \vec{k}_{aT}) (\hat{M}^\nu)^\dagger \bar{\Phi}(x_b, \vec{k}_{bT})] + Y^{\mu\nu}$$

$q_T \ll Q$ $\qquad$ $q_T \simeq Q$

SIDIS

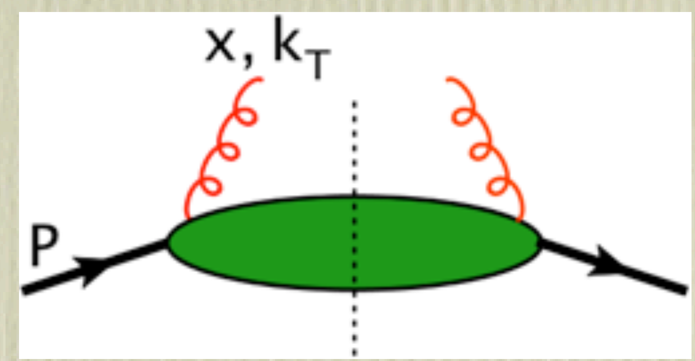
$$W^{\mu\nu} \sim \int d^2k_T d^2p_T\, \delta^{(2)}(\vec{k}_T - \vec{p}_T - \vec{P}_{hT}/z)\, \mathrm{Tr}[\hat{M}^\mu \Phi(x, \vec{k}_T) (\hat{M}^\nu)^\dagger \Delta(z, \vec{p}_T)] + Y^{\mu\nu}$$

Eight Gluon TMDs

$$\Gamma^{ij}(x,\vec{k}_T) = \frac{1}{xP^+}\int \frac{dz^-\, d^2z_T}{(2\pi)^3}\, \mathrm{e}^{ik\cdot z}\langle P,S|\, F^{+i}(0)\,\mathcal{W}[0\,;\,z]\,F^{+j}(z)\,|P,S\rangle\Big|_{z^+=0}$$

$\Gamma^{[T-even]}(x,\vec{k}_T)$			$\Gamma^{[T-odd]}(x,\vec{k}_T)$	
		flip		flip
U	f_1^g	$h_1^{\perp g}$		
L	$g_{1L}^{\perp g}$			$h_{1L}^{\perp g}$
T	$g_{1T}^{\perp g}$		$f_{1T}^{\perp g}$	h_1^g $h_{1T}^{\perp g}$

[Mulders, Rodriues, PRD 63,094021]



* gluonic correspondence to “Boer-Mulders”: T-even
* unpolarized gluons in transversely pol. proton: gluon Sivers function
* gluonic transversity / pretzelosity / wormgears: T-odd
* no chirality
* two collinear PDFs

Processes sensitive to gluon TMDs

Gluon TMDs do not appear in Drell-Yan or SIDIS

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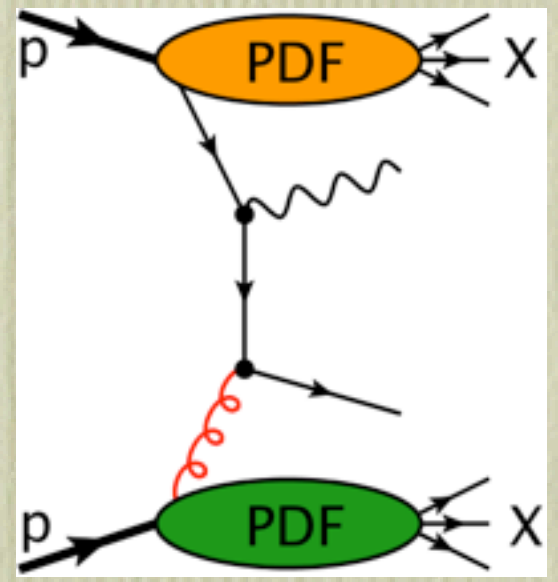

Jet / Hadron production in pp - collisions

Spin dependent processes feasible at RHIC
colored final states: problems with TMD factorization

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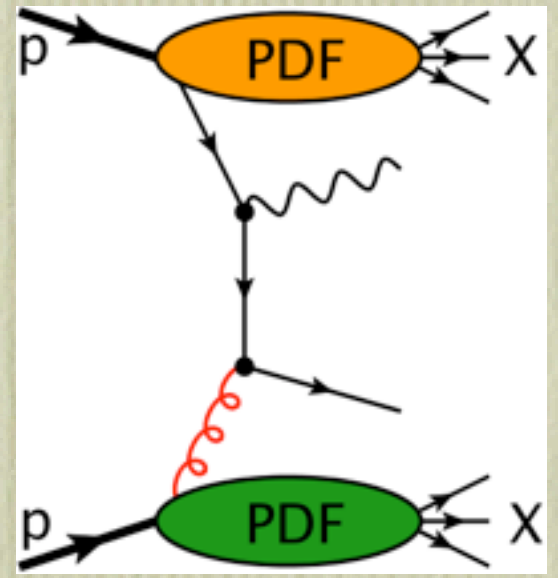

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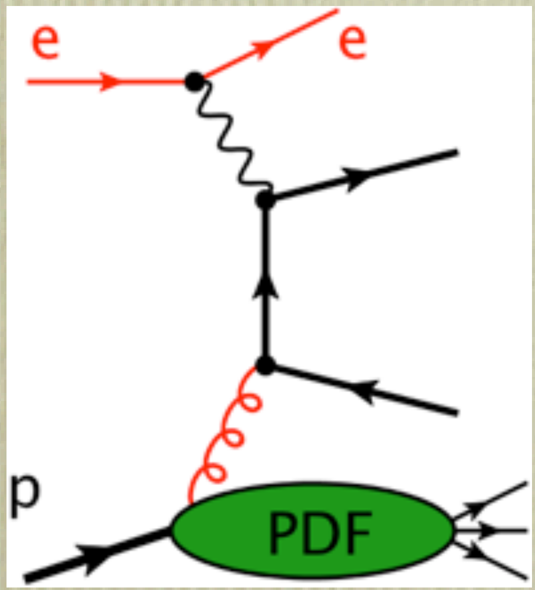


Heavy Quark production in ep - collisions

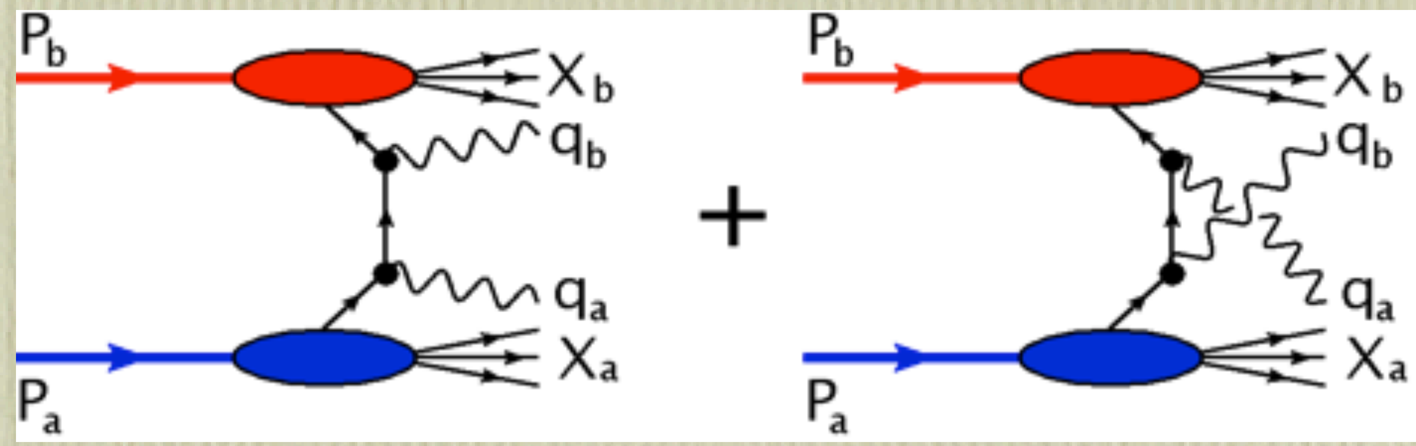
[Boer, Brodsky, Mulders, Pisano, PRL 106, 132001]

TMD factorization ok!
Spin dependent gluon TMDs: EIC
(Nucleon) spin independent gluon TMDs: EIC / HERA(?)

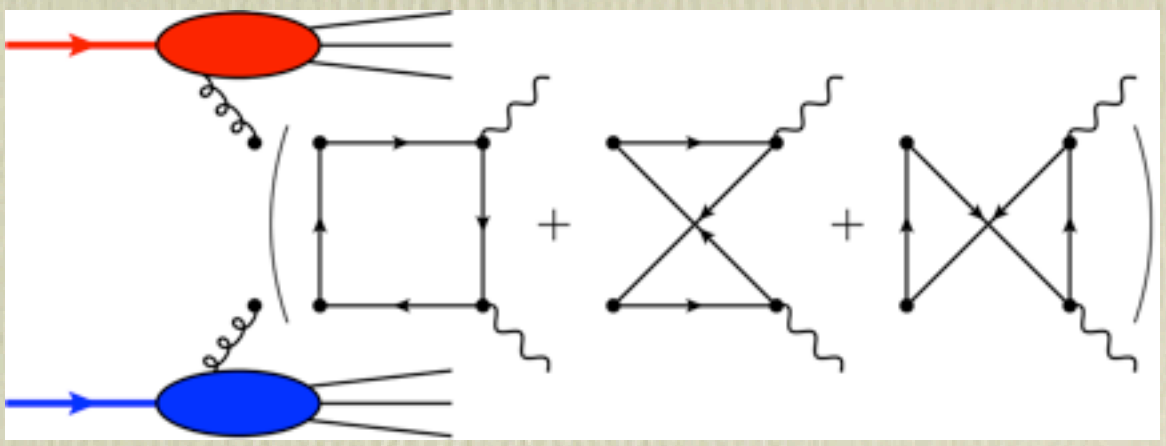
Photon pair production

[Qiu, M.S., Vogelsang, PRL 107, 062001 (2011)]

quark TMDs



gluon TMDs at $O(\alpha_s^2)$



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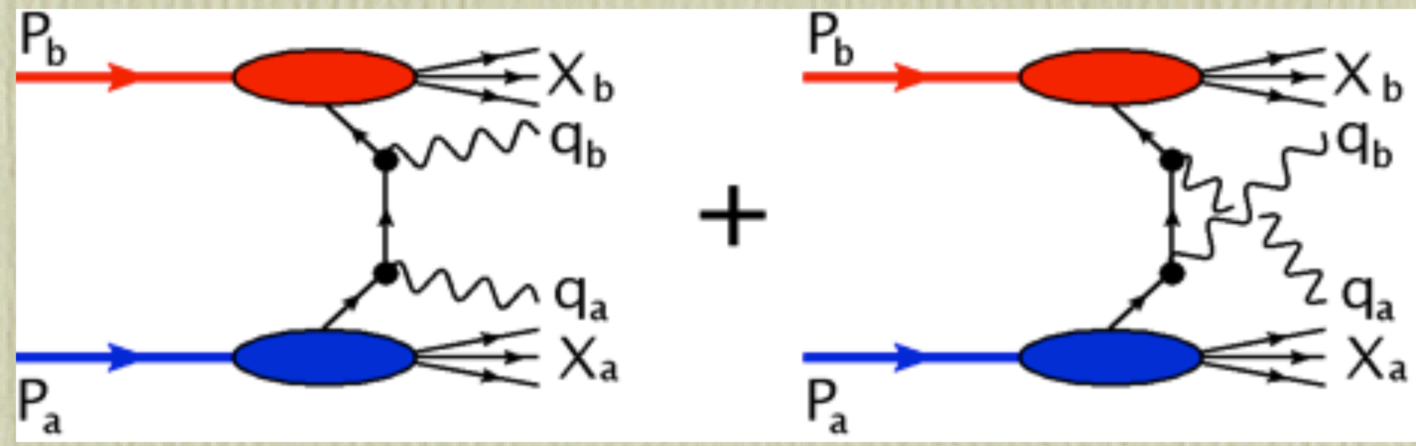

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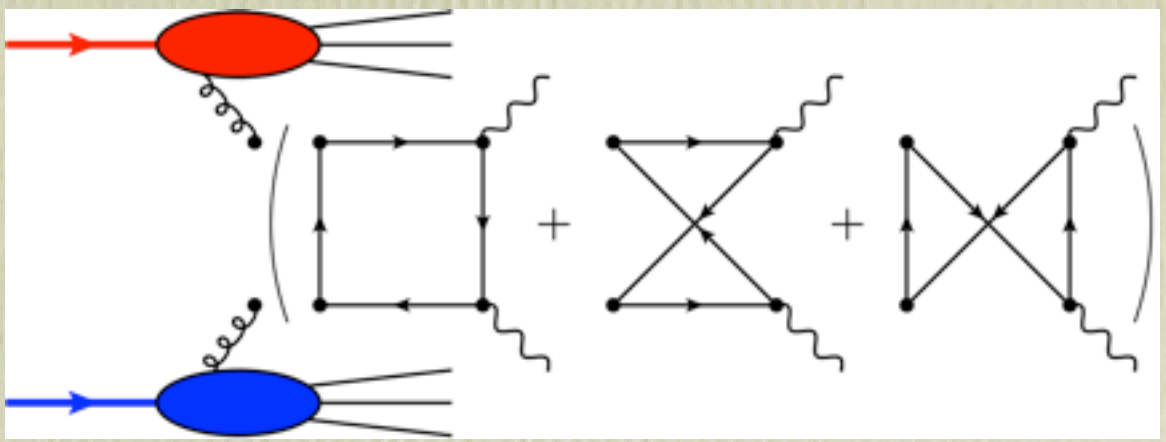

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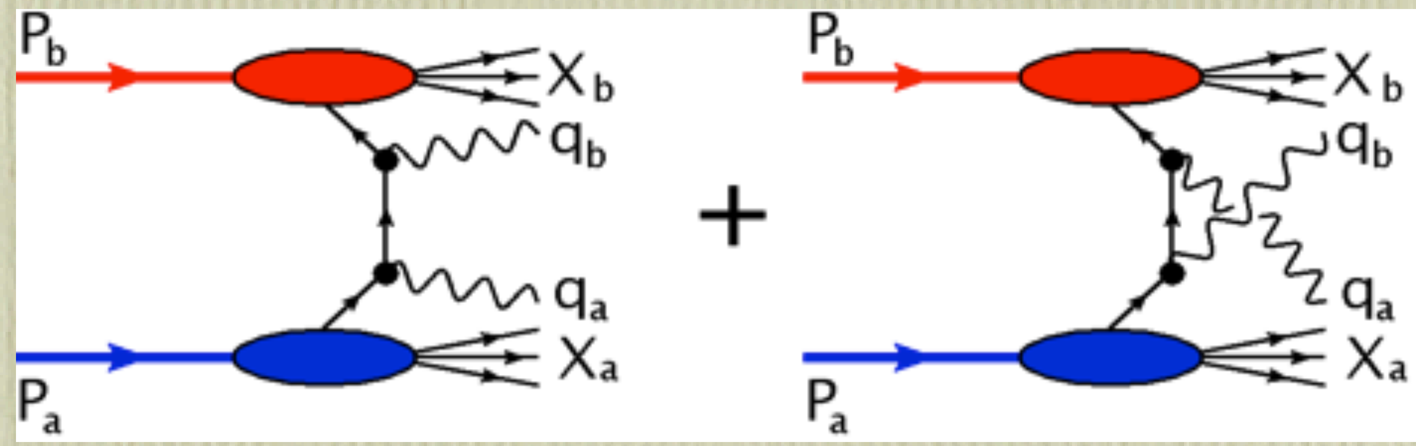

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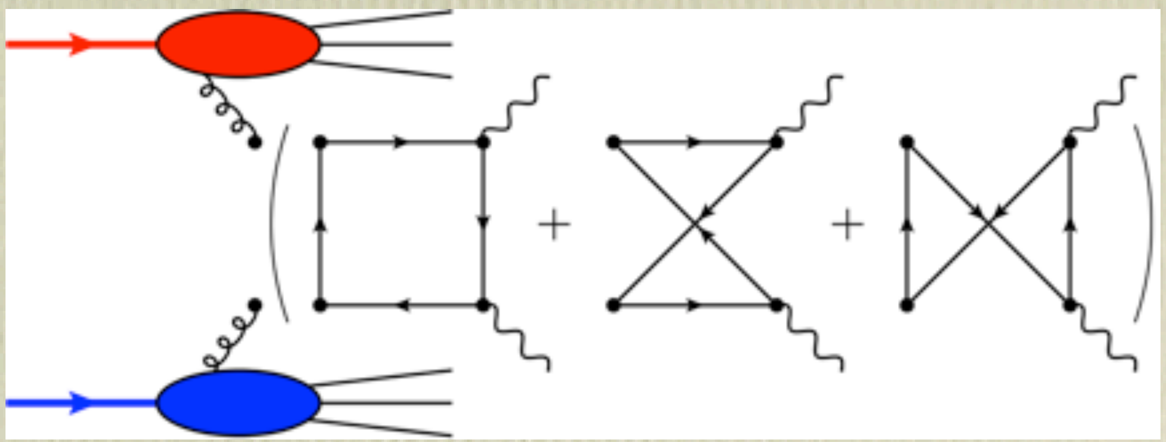

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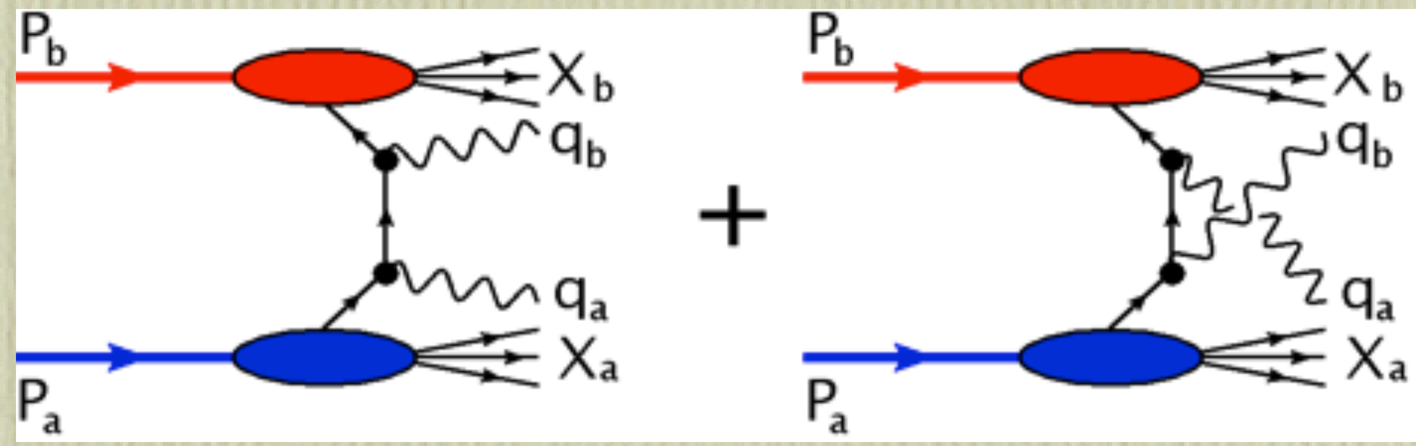

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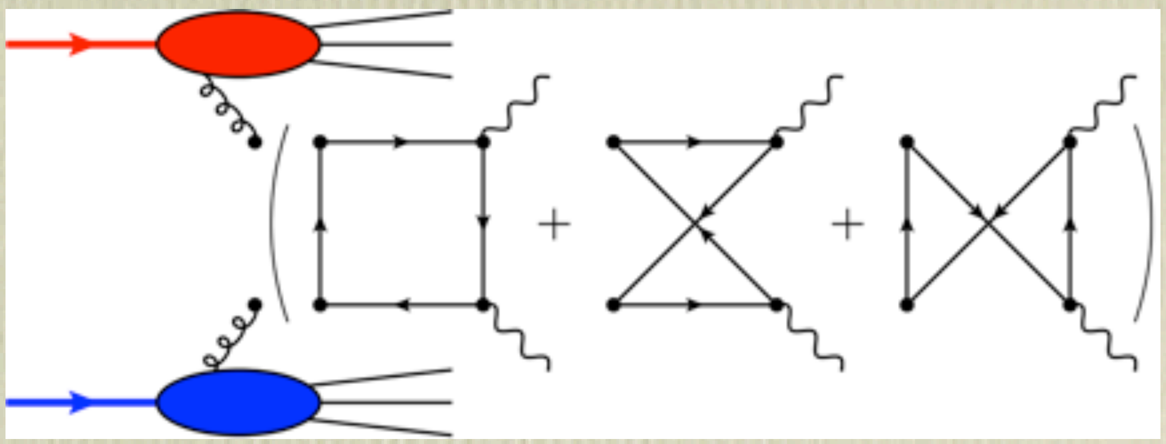

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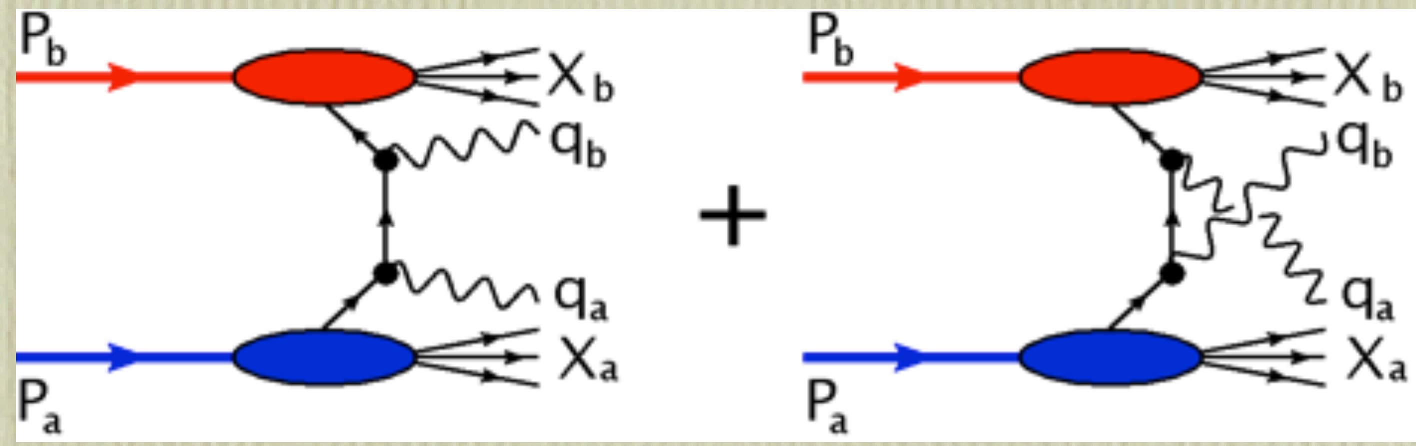

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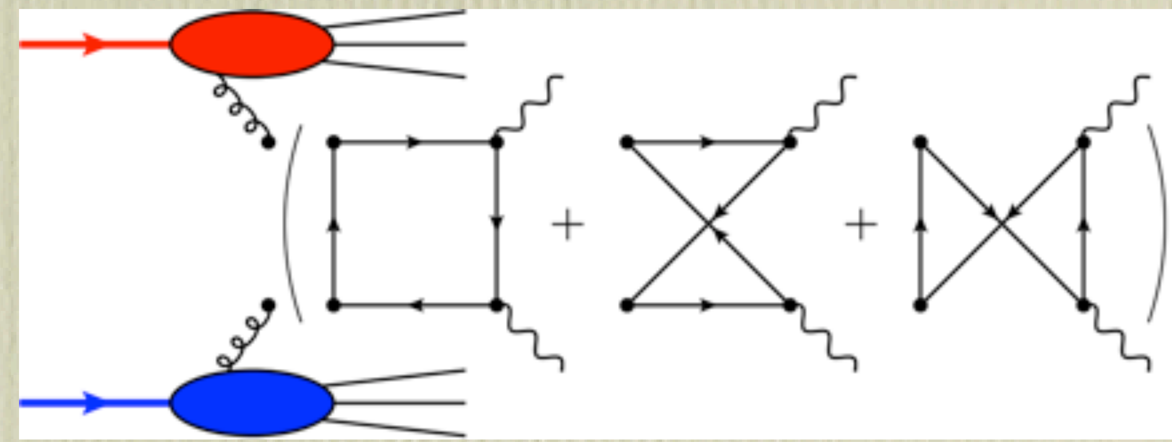

- no colored final state ⇒ TMD factorization ok
- gauge invariance ⇒ box finite ⇒ effectively tree-level
- potentially large gluon distributions
- new azimuthal observables

Unpolarized pp→γγX Cross-Section at q_T << Q

$$\frac{d\sigma_{UU}}{d^4q\,d\Omega} \sim \left(\frac{2}{\sin^2\theta}\right)\left((1+\cos^2\theta)[f_1^q \otimes f_1^{\bar{q}}] + \cos(2\phi)\sin(2\theta)[h_1^{\perp q} \otimes h_1^{\perp \bar{q}}]\right)$$

quark contributions → almost identical to DY

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- requires p_T & isolation cuts for the photons
- powerful in combination with DY ➙ map out quark TMDs in DY → gluon TMDs in γγ

RHIC energy: $\sqrt{S} = 500\,\mathrm{GeV}$

Positivity bounds

$$|h_1^{\perp,g}| \le \frac{2M^2}{k_T^2} f_1^g \qquad |h_1^{\perp}, q| \le \frac{M}{k_T} f_1^q$$

Gaussian ansatz:

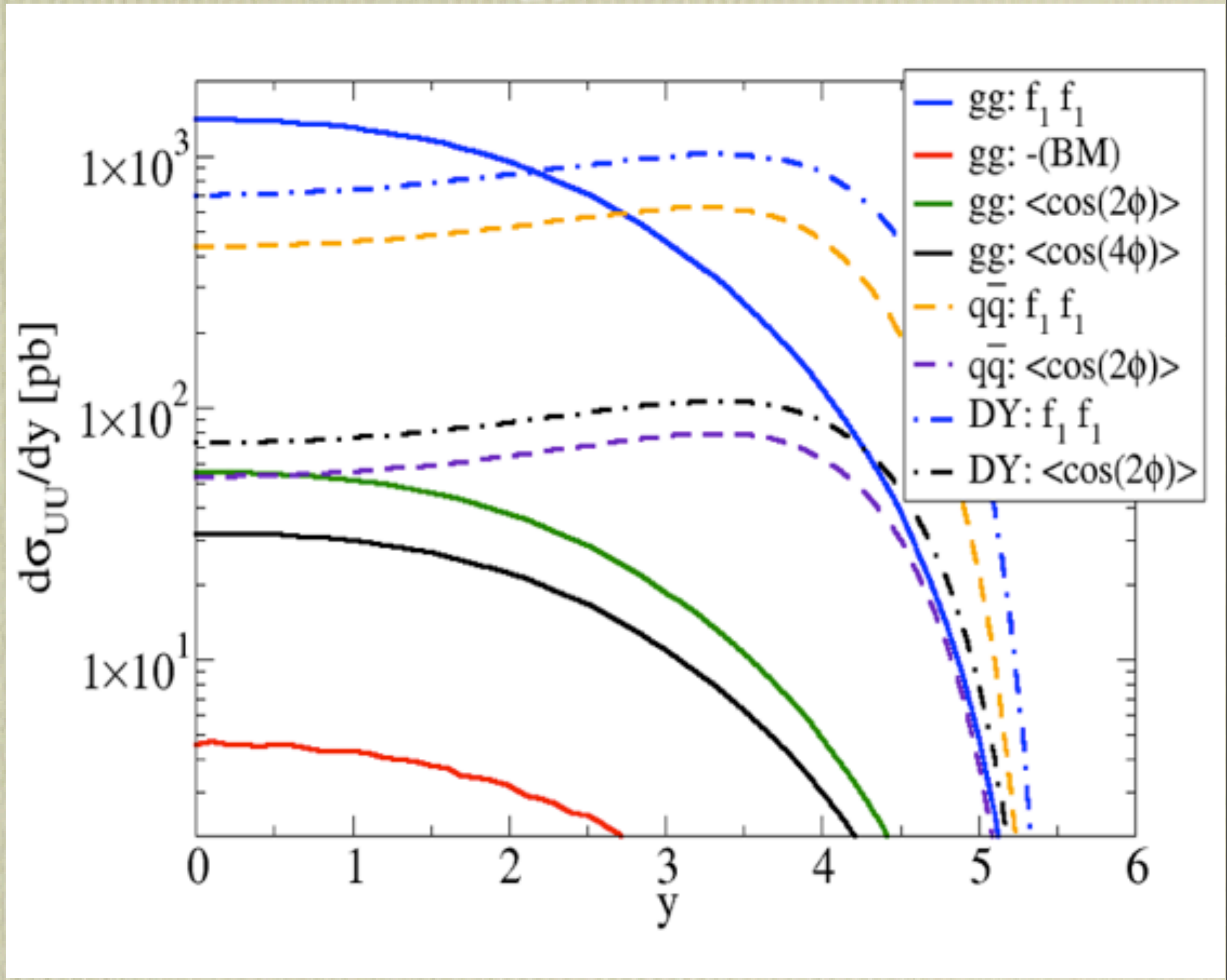
$$f_1^{q/g}(x, k_T^2) = f_1^{q/g}(x)\, \mathrm{e}^{-k_T^2/\langle k_{T,q/g}^2 \rangle}$$

Gaussian widths:

$$\langle k_{T,q}^2 \rangle = \langle k_{T,g}^2 \rangle = 0.5\,\mathrm{GeV}^2$$

p_T-cuts for each photon:

$$p_T^\gamma > 1\,\mathrm{GeV}$$



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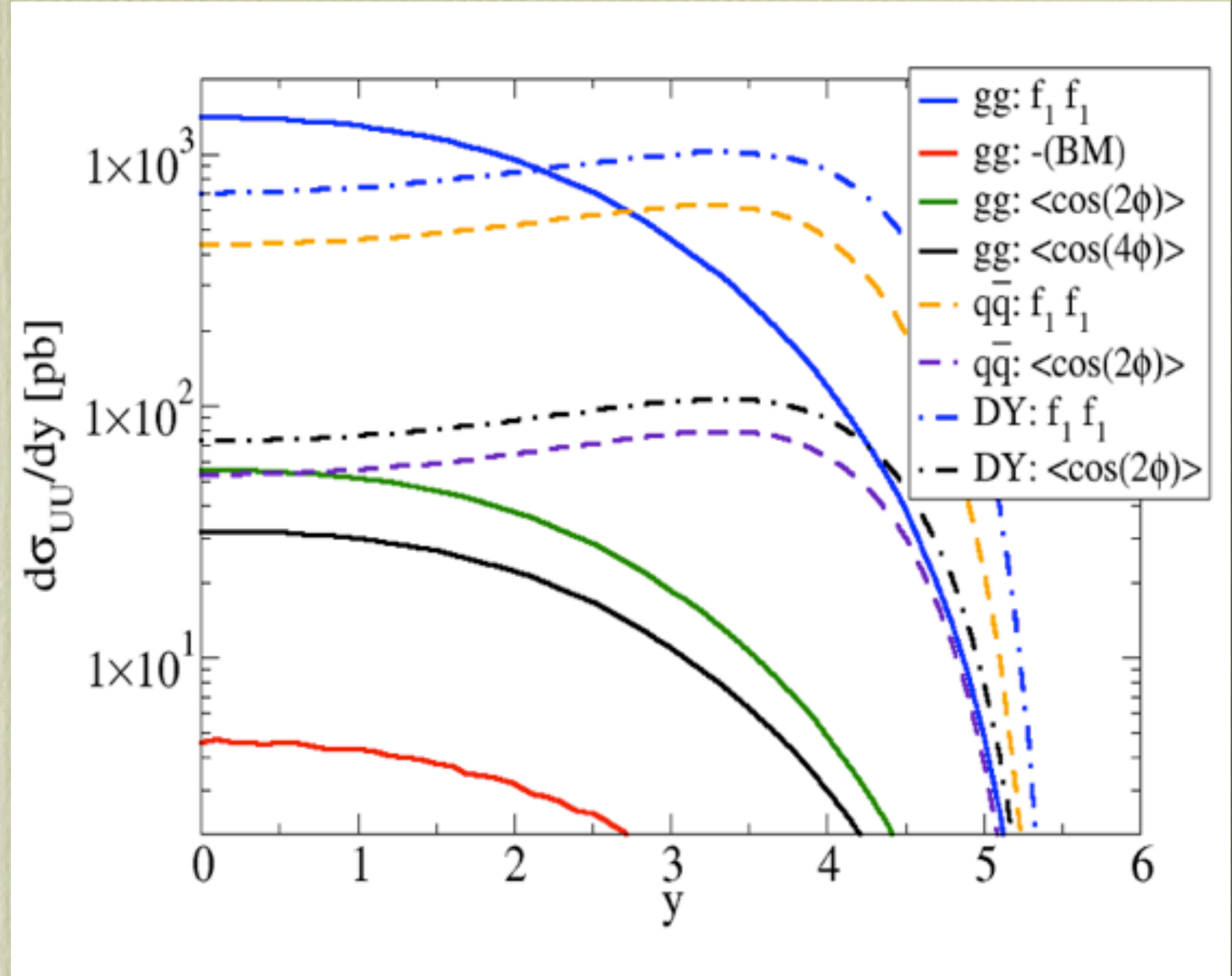

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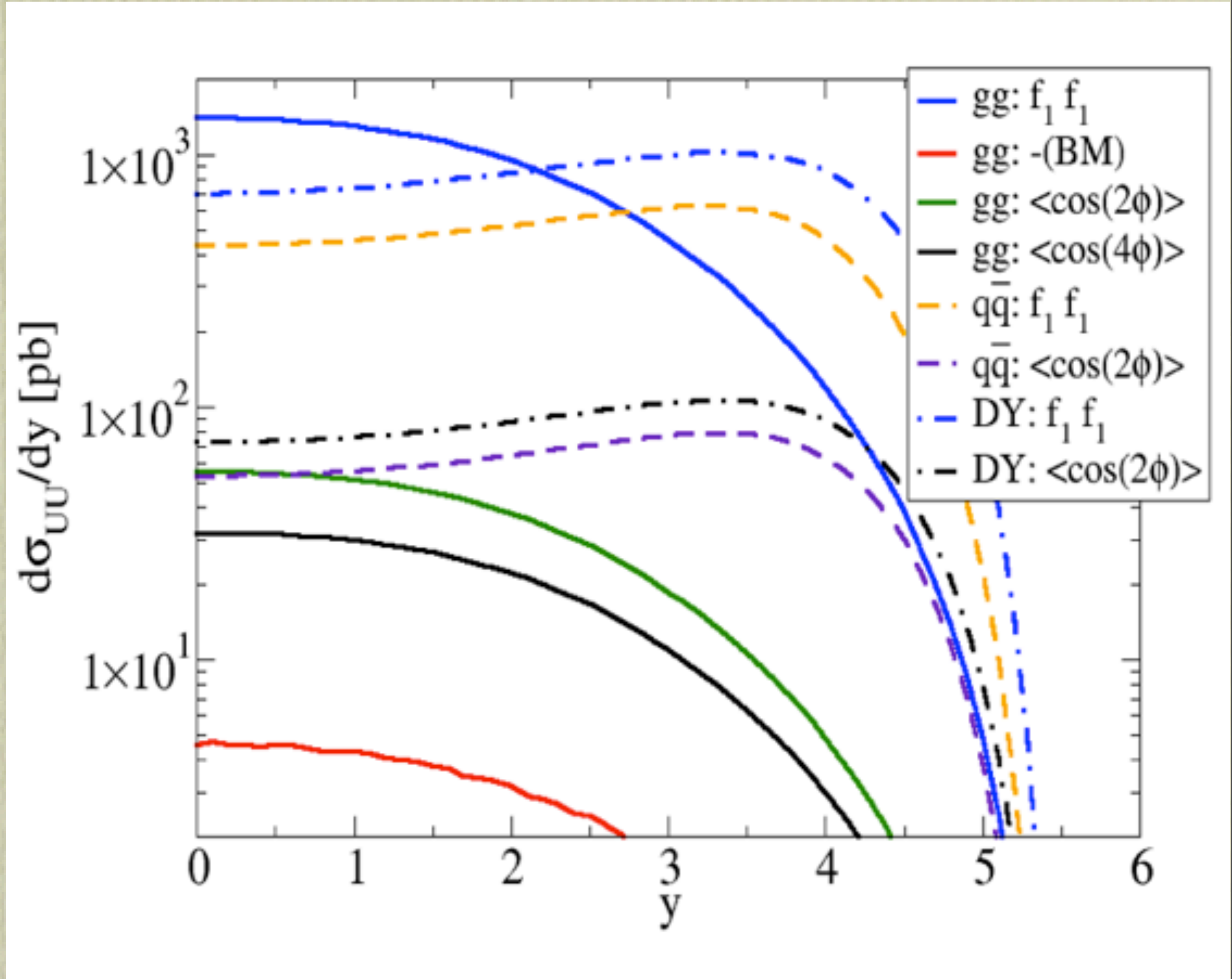

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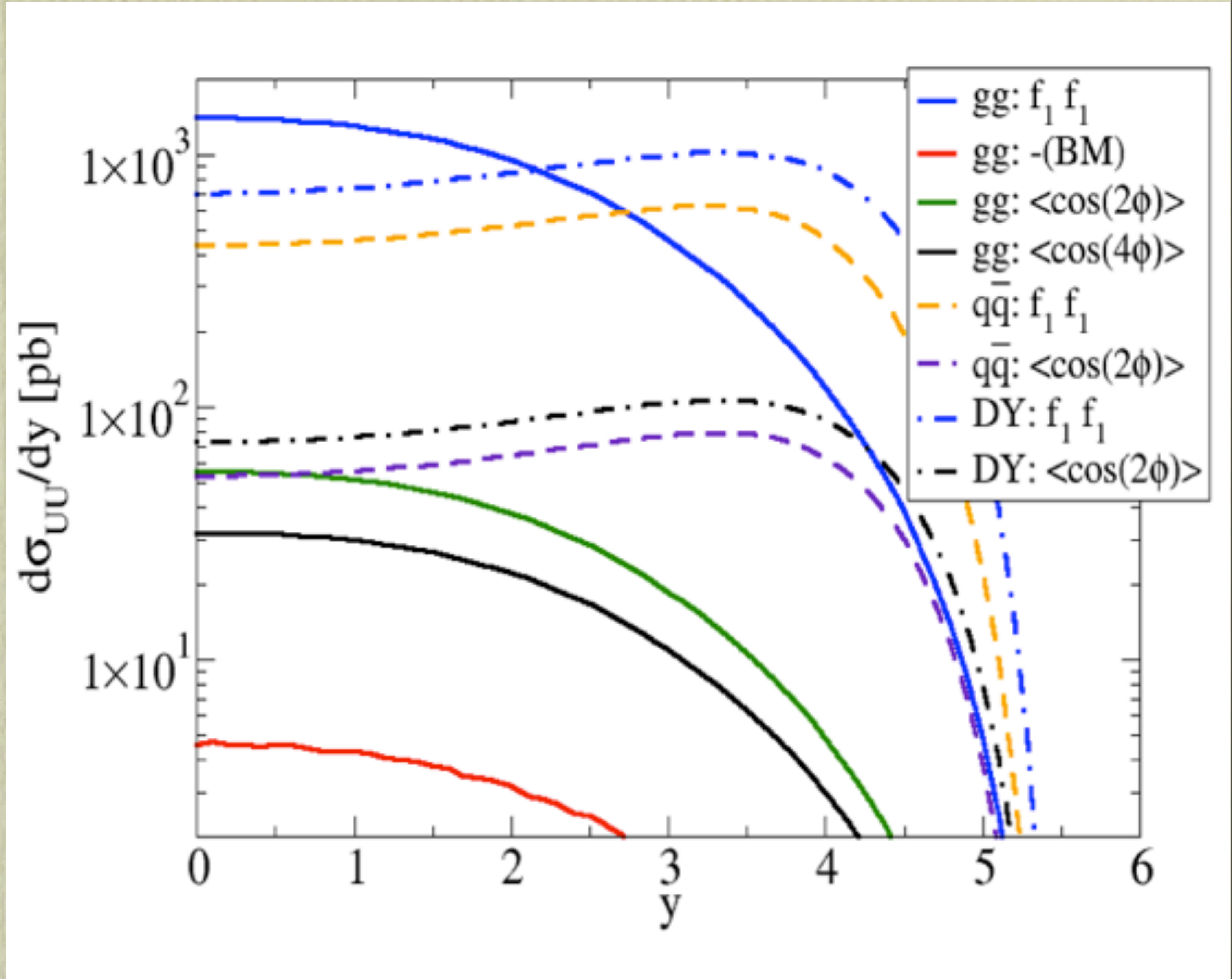

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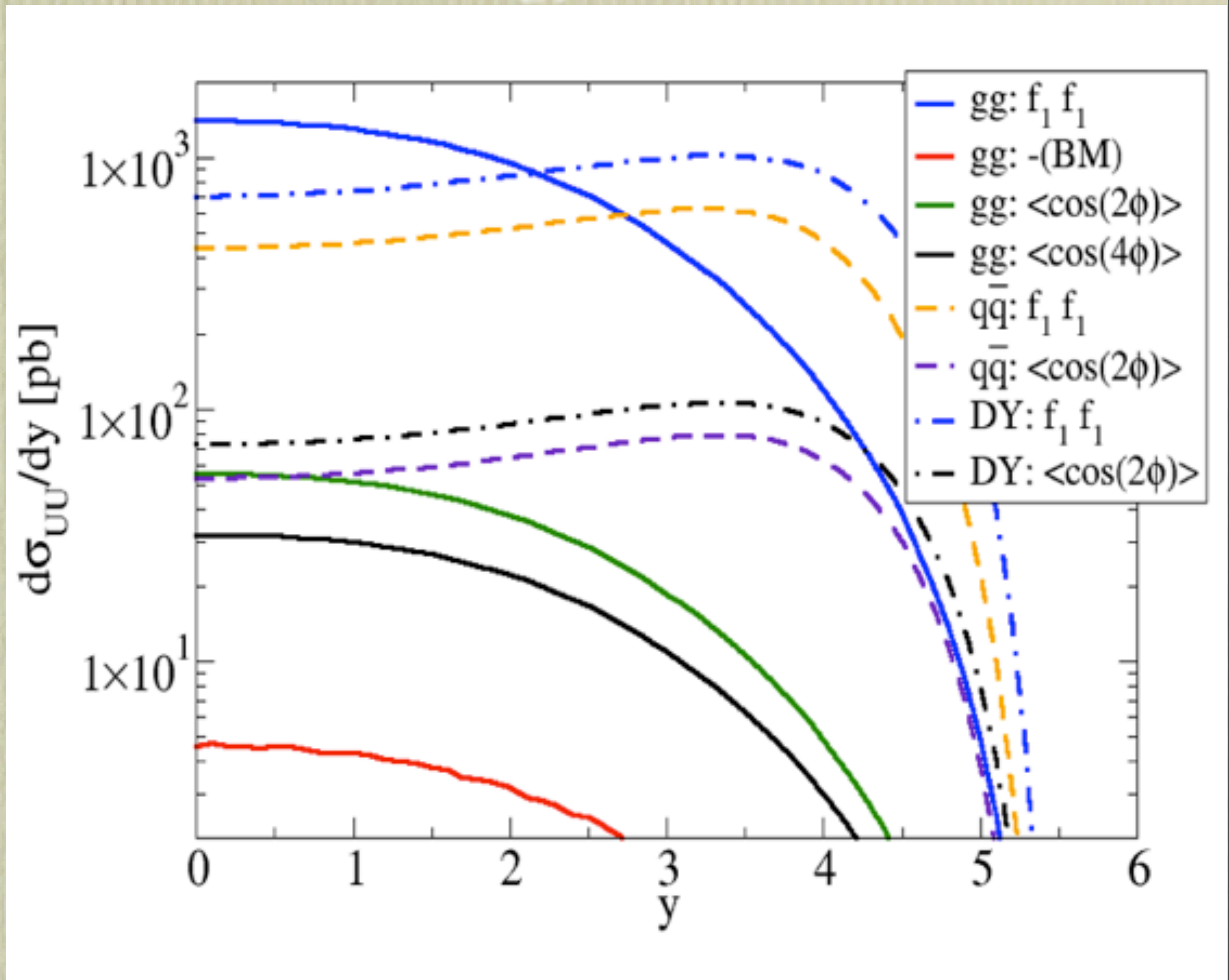

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- cos(2ϕ) → determination of sign of $h_1^{\perp g}$

Gluon Sivers Effect

(Transverse) Spin dependent photon pair cross section:

$$\frac{d\sigma_{TU}}{d^4q\,d\Omega} \sim S_T \sin\phi_S \Big[\frac{2}{\sin^2\theta}(1+\cos^2\theta)\,[f_{1T}^{\perp,q} \otimes f_1^{\bar{q}}] + \Big(\frac{\alpha_s}{2\pi}\Big)^2 \Big(\mathcal{F}_1\,[f_{1T}^{\perp,g} \otimes f_1^g] + \mathcal{F}_2\,[h_1^g \otimes h_1^{\perp,g}] + \mathcal{F}_2\,[h_{1T}^{\perp,g} \otimes h_1^{\perp,g}]\Big)\Big] + \ldots$$

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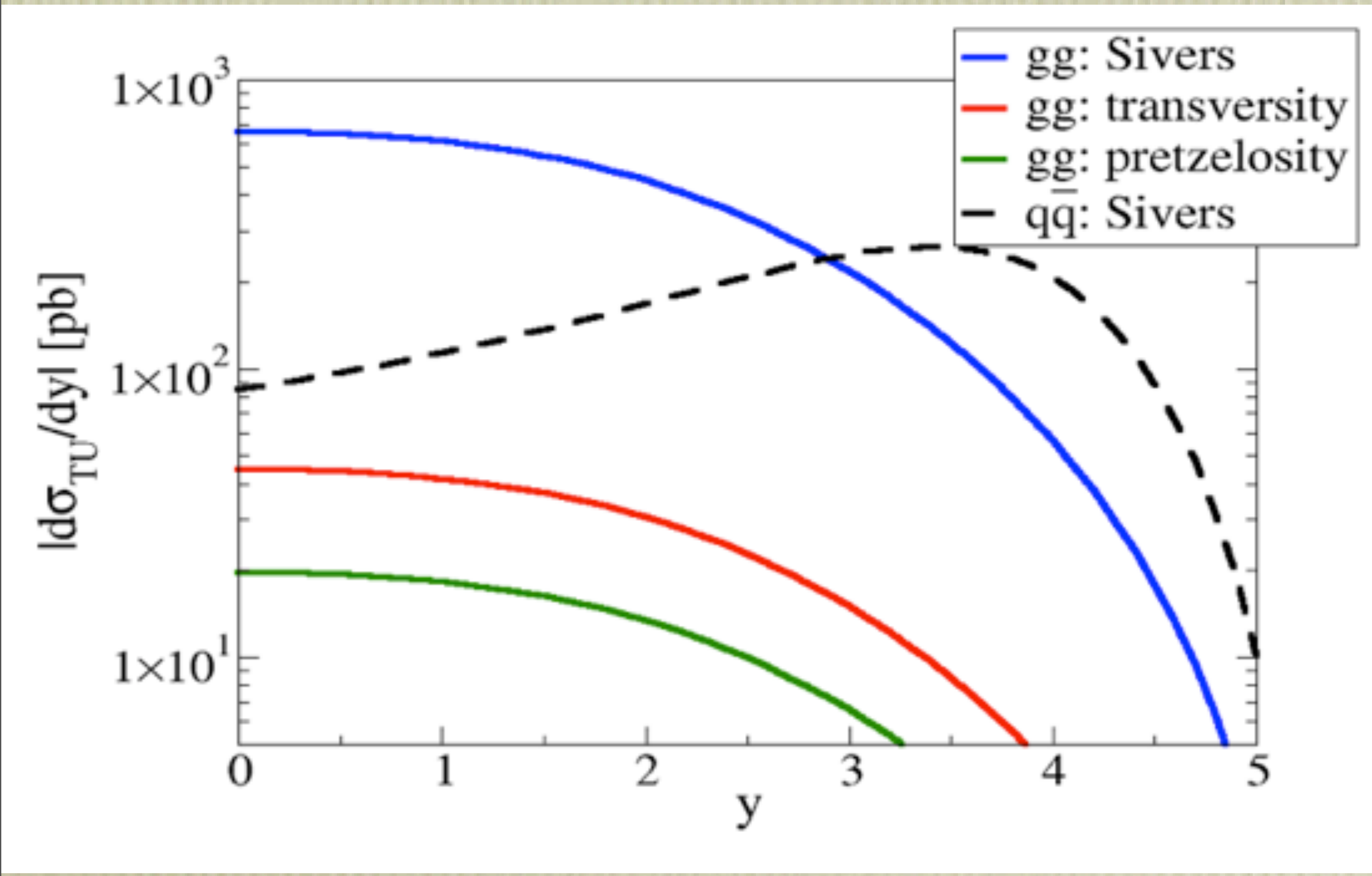

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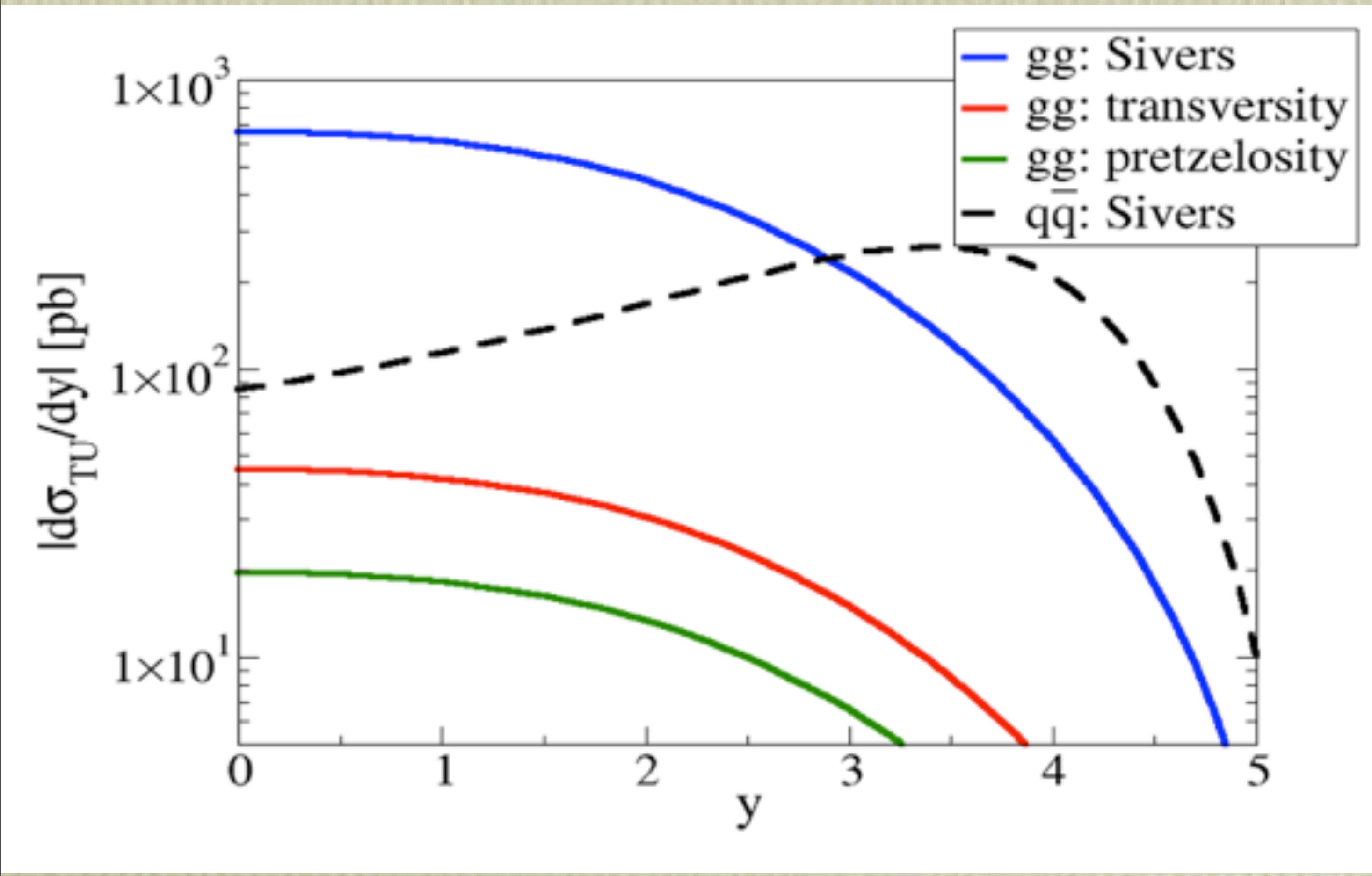

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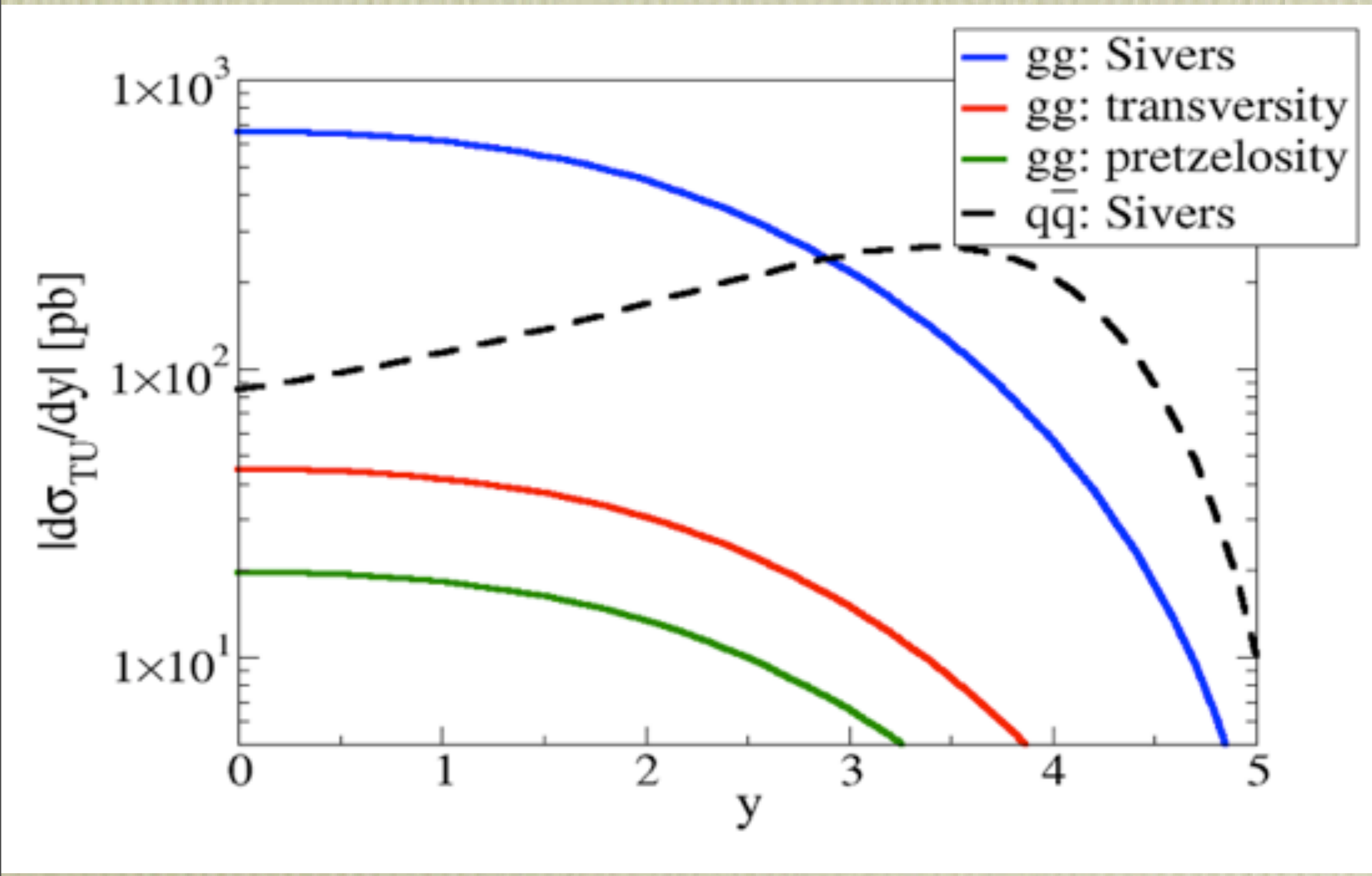

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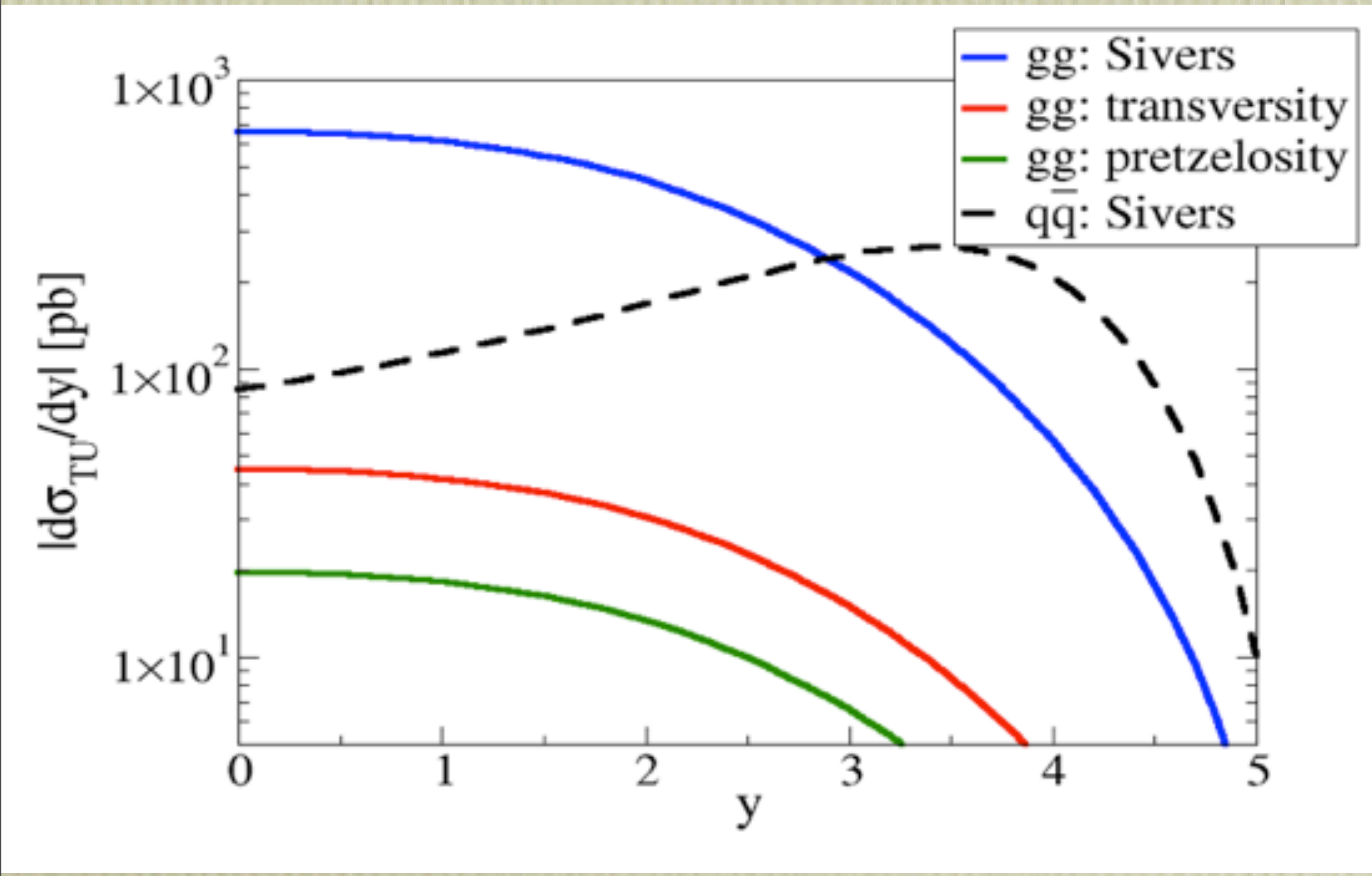

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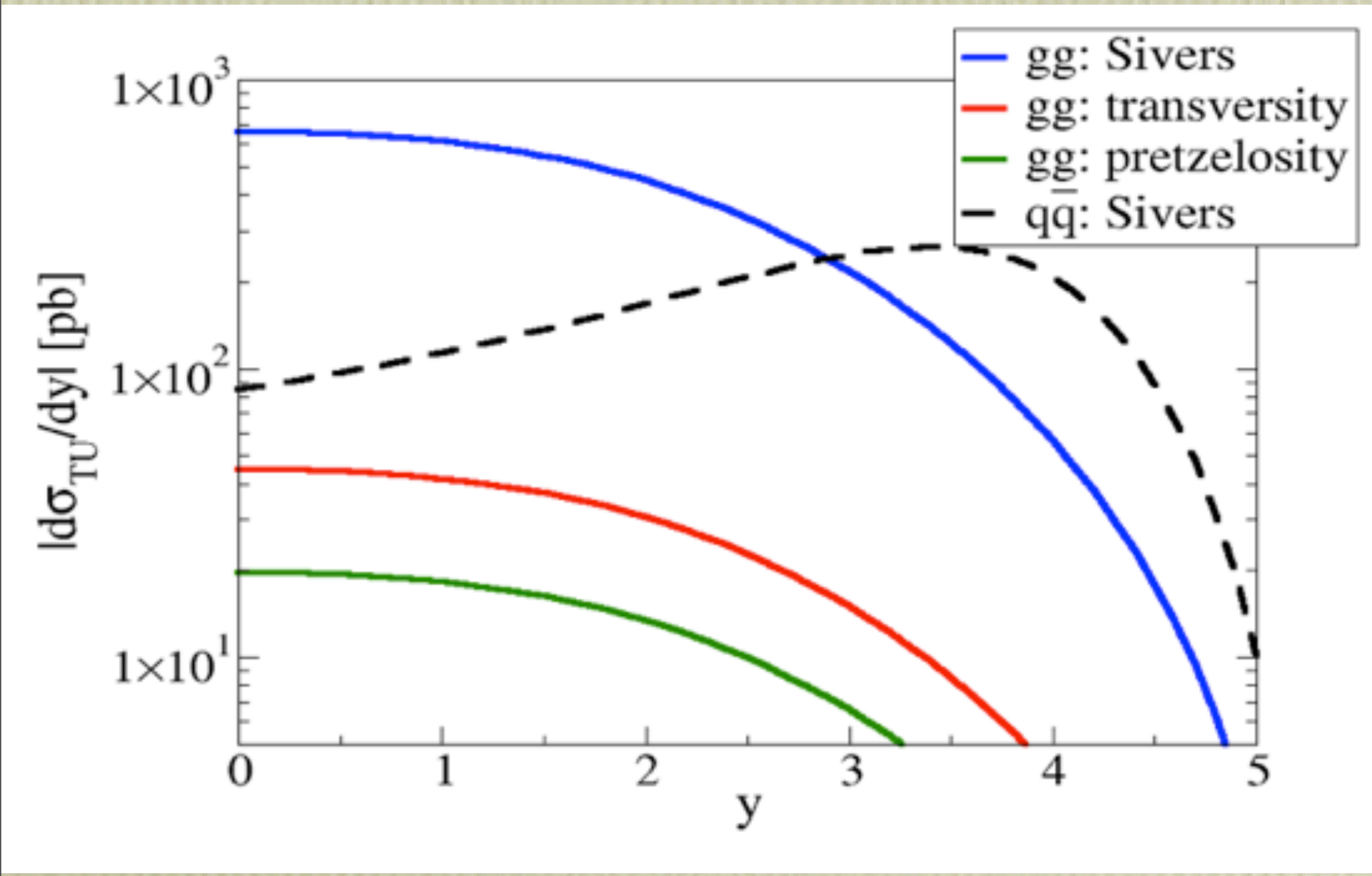

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- Effects by gluon "transv. / pretzel." small

Linearly polarized gluons and Higgs production

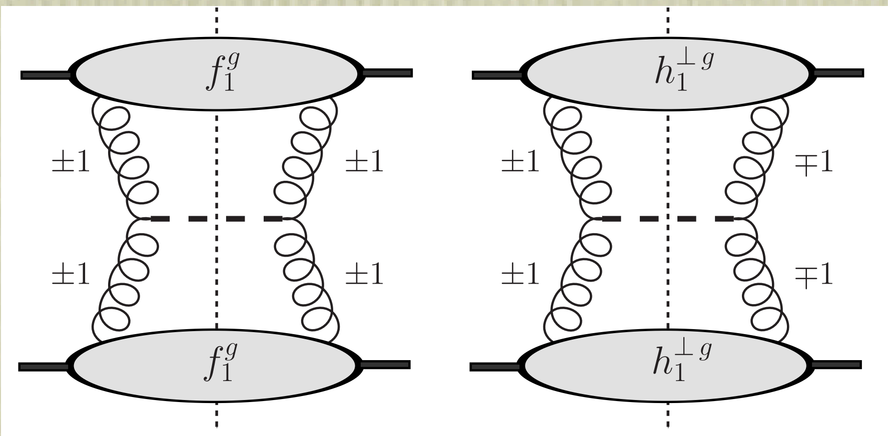
[Boer, den Dunnen, Pisano, M.S., Vogelsang, PRL 108, 032002 (2012)]

corresponding collinear resummation studies: [Nadolsky et al., Catani, de Florian, Grazzini; Sun, Xiao, Yuan]

Can gluonic TMDs be useful for the LHC?

Once a scalar particle (Higgs!?) is found........ want to determine its parity.

pure Higgs production via top-quark loop



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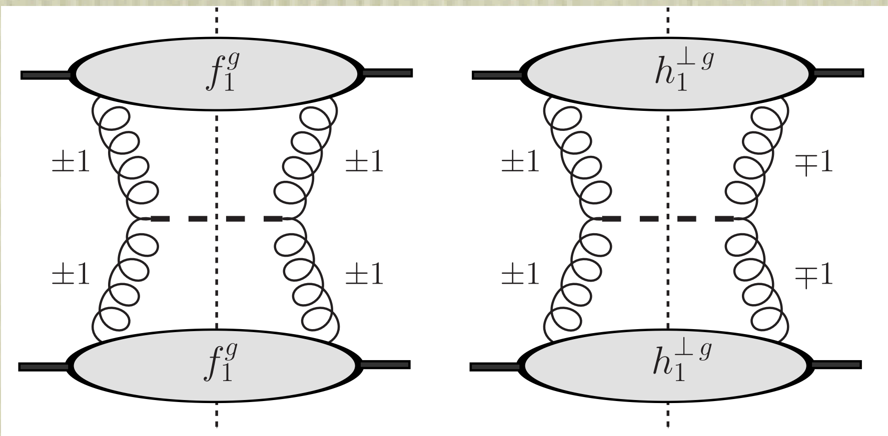

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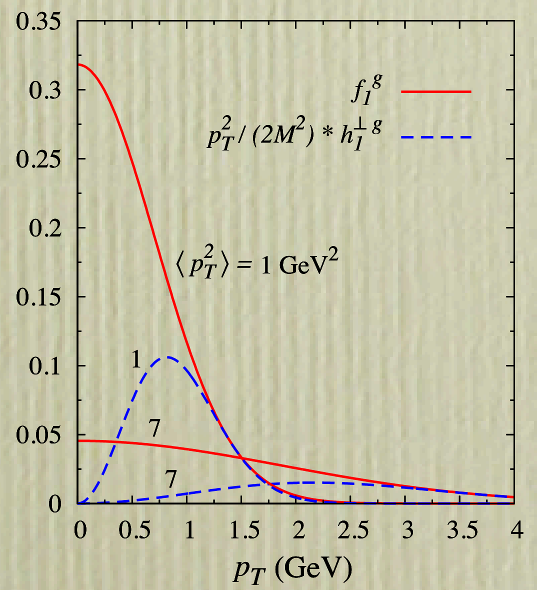

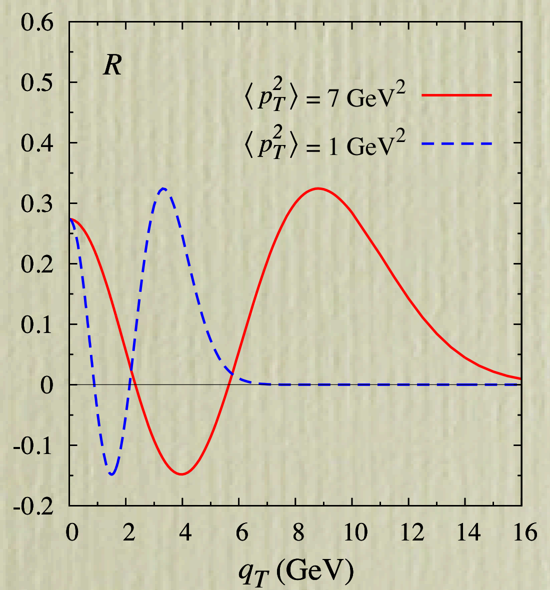

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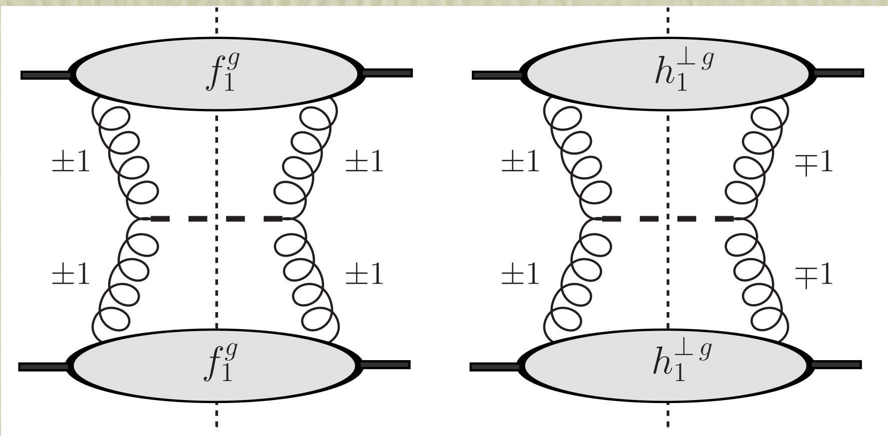

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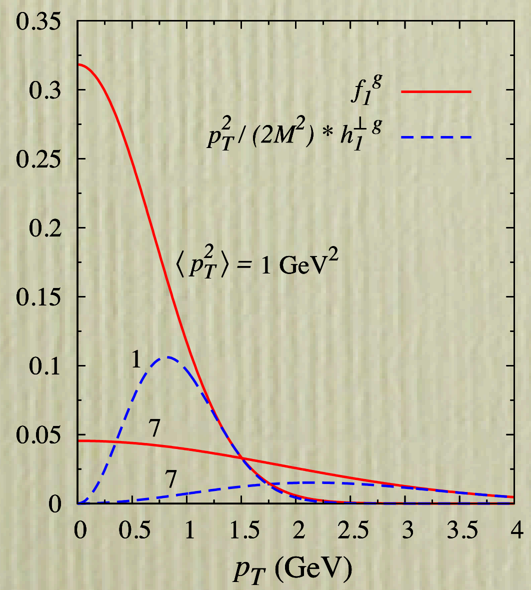

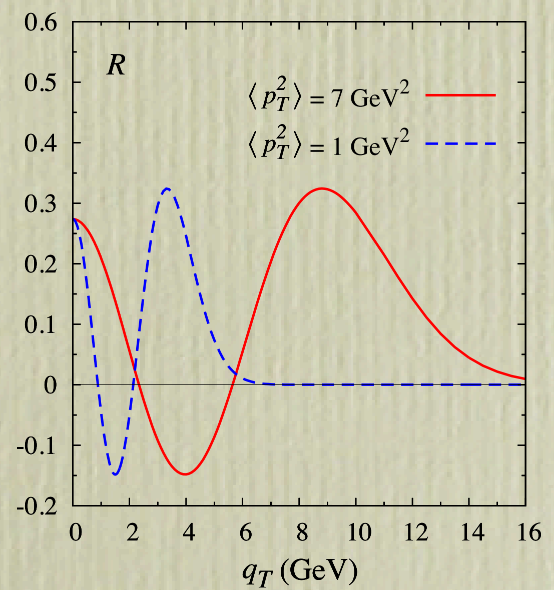

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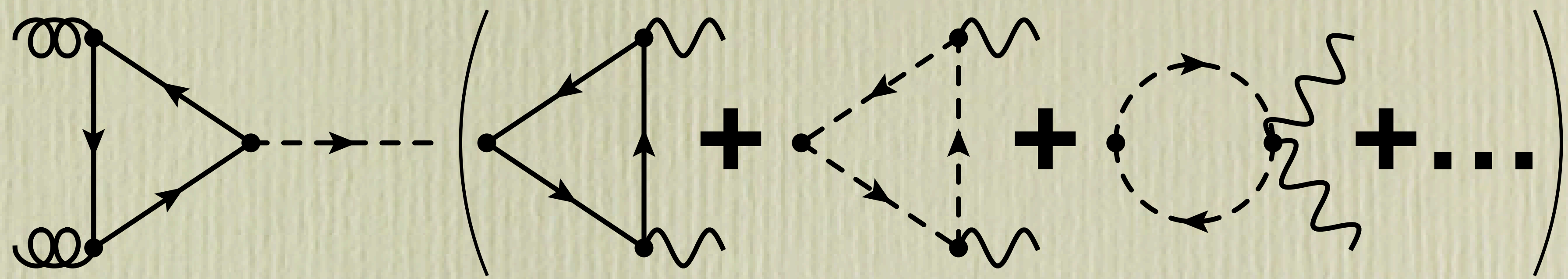
linearly polarized gluons sensitive to Higgs parity

$$[f_1^g \otimes f_1^g] \pm [h_1^{\perp g} \otimes h_1^{\perp g}]$$

+: scalar Higgs   -: pseudoscalar Higgs

precise q_T measurement may offer a way to determine Higgs parity

Including Higgs decay: gg → H/A → γγ



ϕ - integrated cross section of Higgs + box:

$$\int d\phi \frac{d\sigma^{gg}}{d^4q\, d\Omega} \propto \bar{\mathcal{F}}_1 \, [f_1^g \otimes f_1^g] + \bar{\mathcal{F}}_2 \, [h_1^{\perp g} \otimes h_1^{\perp g}]$$

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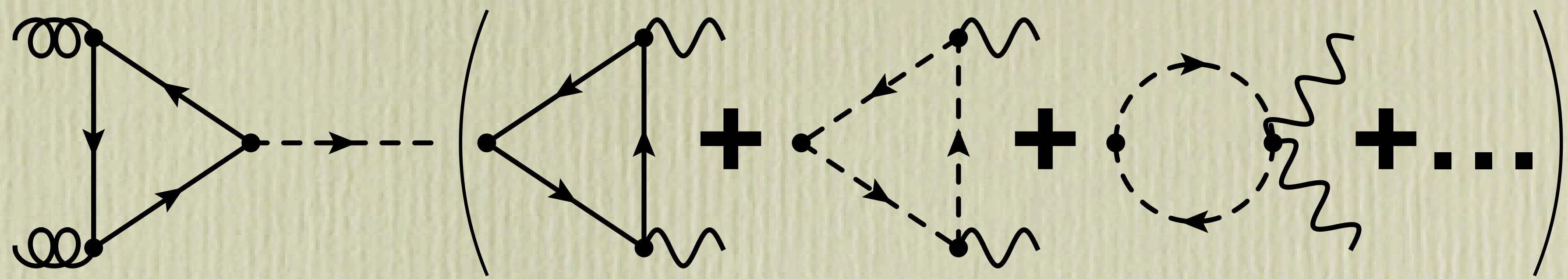

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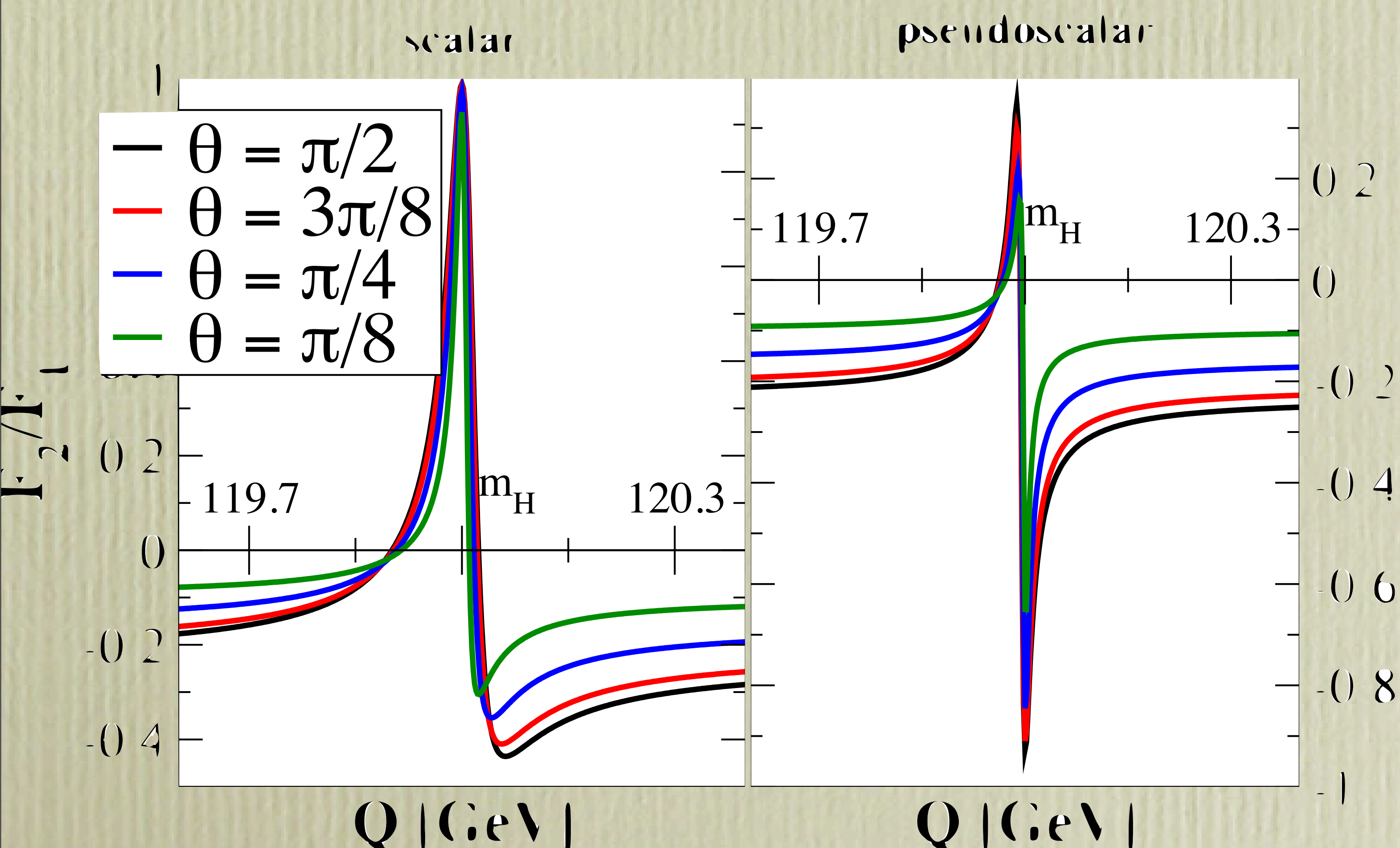


Q ≠ m_H: $\bar{\mathcal{F}}_1 \gg \bar{\mathcal{F}}_2$

box dominant

Q ~ m_H : $\bar{\mathcal{F}}_1 \simeq \bar{\mathcal{F}}_2$

Higgs dominant (pole of the propagator)

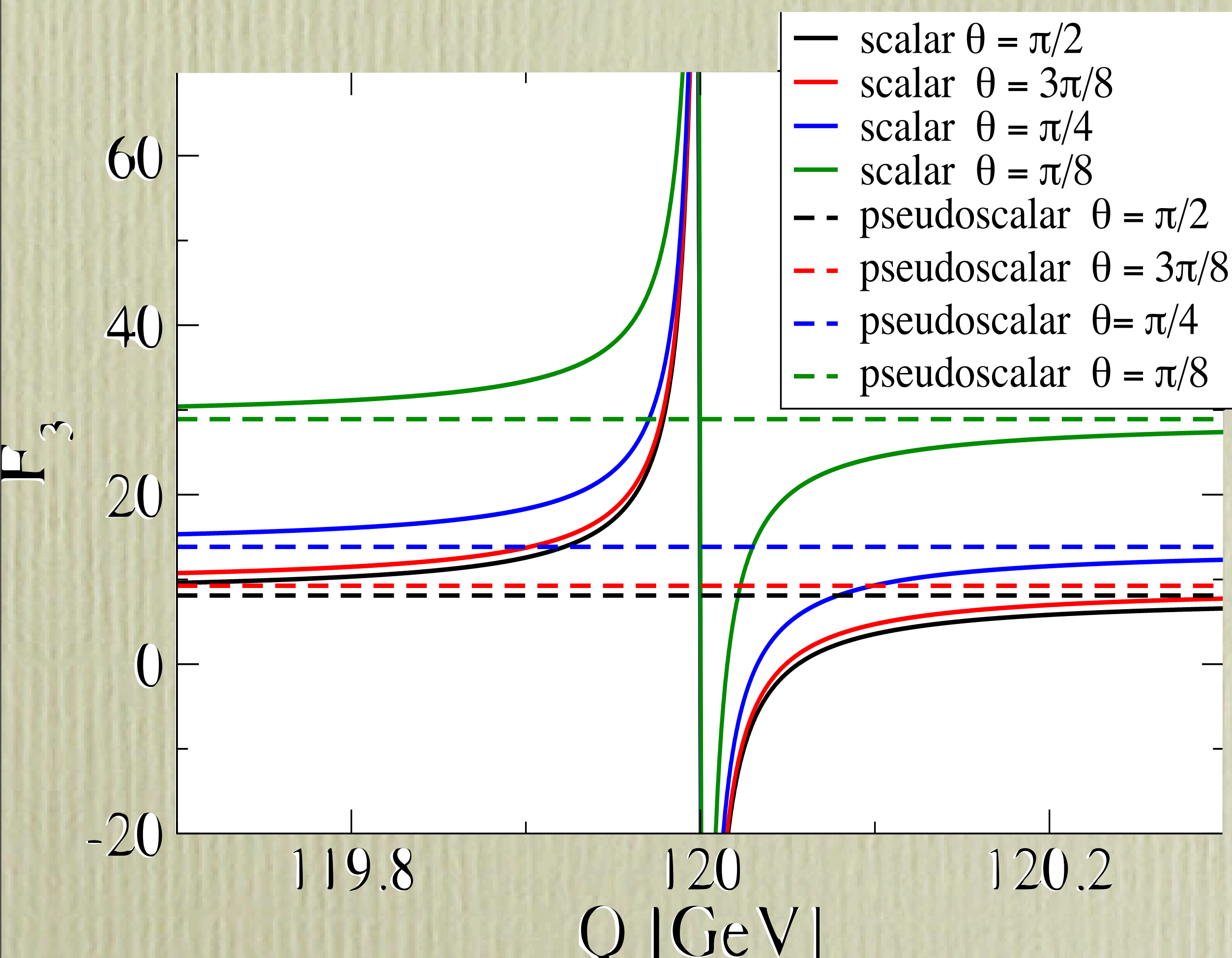
Sign signature preserved at the pole!
small total Higgs width → good Q resolution

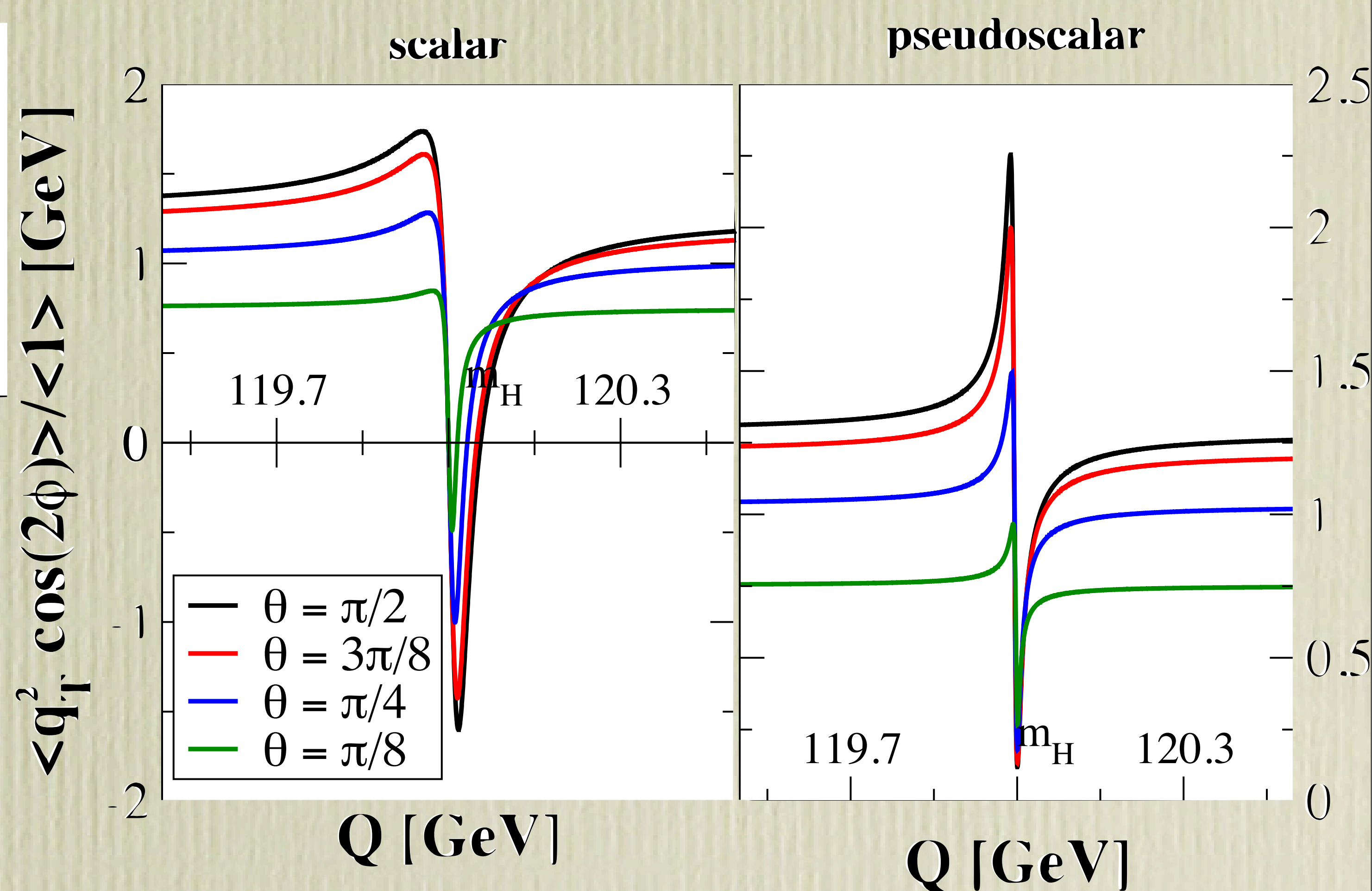
May use also azimuthal cos(2φ) modulation...

$$\langle q_T^2 \cos(2\phi)\rangle = \int d^2q_T d\phi\, q_T^2 \cos(2\phi) \frac{d\sigma}{d^4q\, d\Omega} \sim \bar{\mathcal{F}}_3(\theta, Q^2) \left[f_1^g \otimes h_1^{\perp g} + h_1^{\perp g} \otimes f_1^g \right]$$

scalar Higgs contributes to $\mathcal{F}_3$, pseudoscalar doesn't

→ offers alternative determination of Higgs parity.





Summary

- Gluon TMDs from Photon Pair Production
- Gluon Boer-Mulders effect may offer a way to determine parity of the Higgs boson at LHC
- Gluon Sivers- and Boer-Mulders effect may be feasible at RHIC (if $\neq 0$)

To-do list

Work out other spin observables in photon pair production

Work out other final states relevant for LHC,
e.g. $gg \rightarrow ZZ, WW, Z\gamma$, etc.

Work out a more realistic k_T-behaviour of $h_1^{\perp g}$