Photon Pair Production

Marc Schlegel

Institute for Theoretical Physics
University of Tuebingen

in collaboration with Jianwei Qiu & Werner Vogelsang

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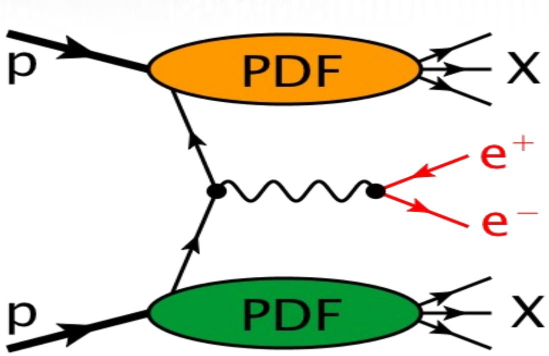
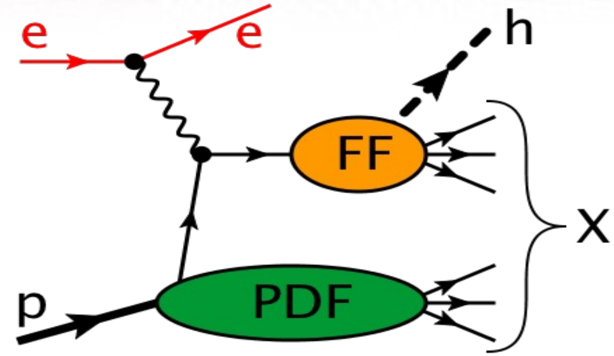
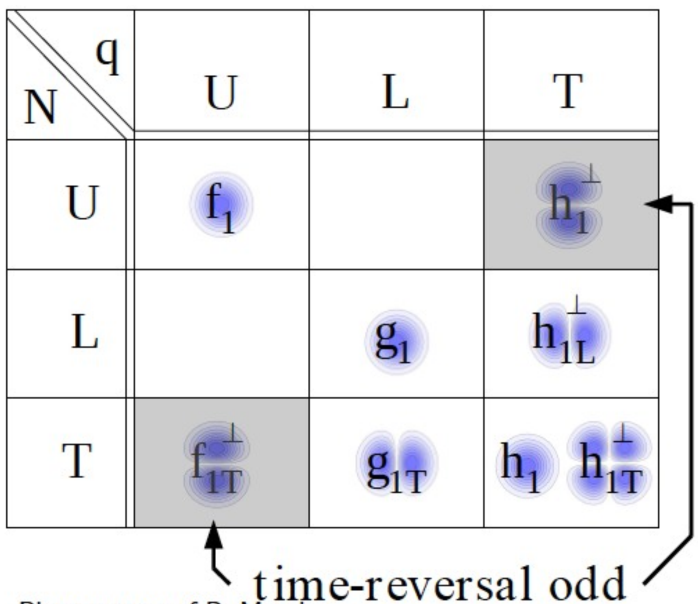
Drell-Yan & SIDIS





<u>Suitable to extract quark - TMDs</u>

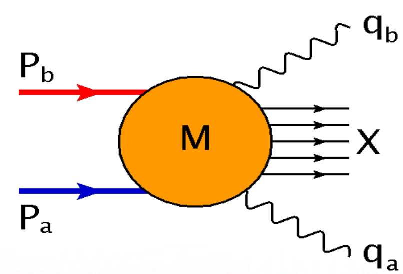


Plot courtesy of B. Musch

- SIDIS → measurements at HERMES, COMPASS, Jlab...
  → need Fragmentation Functions
- DY → Convolution of 2 TMDs
  → $p\bar{p}$: Valence-quarks
  pp : Sea-quarks (RHIC)
- Sign-change of T-odd TMDs

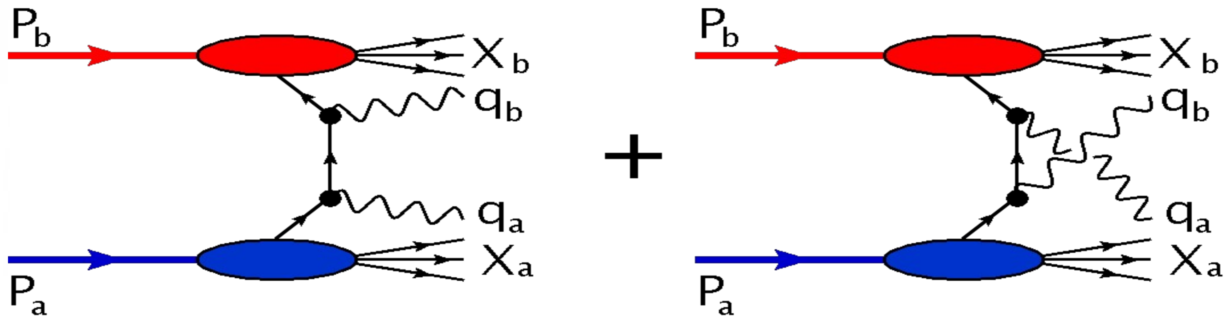
→ *no gluon TMDs!*

Photon Pair Production



Photon Pairs from $q\bar{q}$-channel

Parton model tree-level at $O(\alpha_s^0)$ → quark-TMDs!



Only relevant at very small q_T: $\Lambda_{QCD} \sim q_T \ll Q$

$$\left(\frac{d\sigma}{d^4q\, d\Omega}\right) \propto \int d^2k_{aT} \int d^2k_{bT}\, \delta^{(2)}(\vec{k}_{aT} + \vec{k}_{bT} - \vec{q}_T)\, \mathrm{Tr}\left[\Phi(x_a, \vec{k}_{aT})\, H(x_a, x_b, q_a, q_b)\, \bar{\Phi}(x_b, \vec{k}_{bT})\, H^\dagger\right] + \mathcal{O}(\tfrac{M}{Q})$$

k_T - correlator:

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

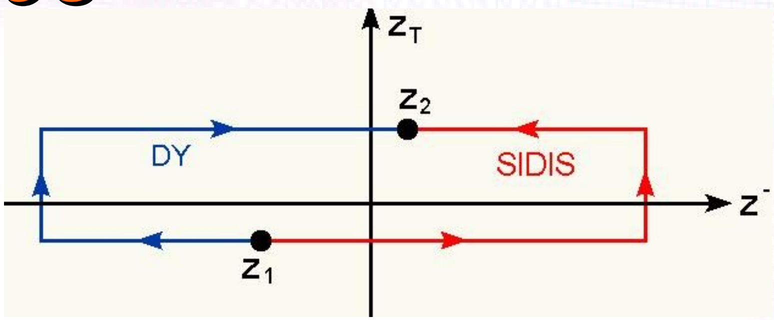
Main result of the TMD tree-level formalism:

$$\left(\frac{d^6\sigma^{hh\to\gamma\gamma X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q) = \frac{2}{\sin^2\theta} \left(\frac{d\sigma^{hh\to l^+l^- X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q \,|\, e_q \to e_q^2)$$

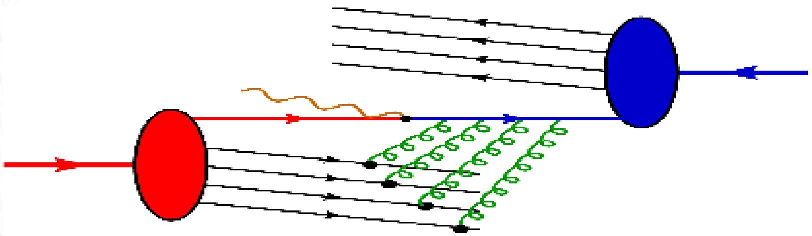
Wilson lines

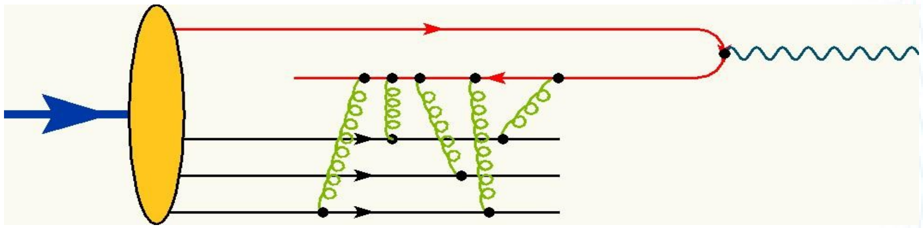
Wilson line process-dependent in DY/SIDIS:

$$\mathcal{W}[z_1; z_2] = \mathcal{P}e^{-ig\int_{z_1}^{z_2} ds\cdot A(s)}$$

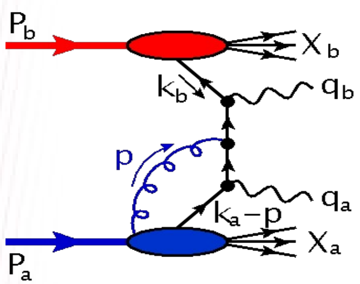


Physics: Initial / Final state interactions

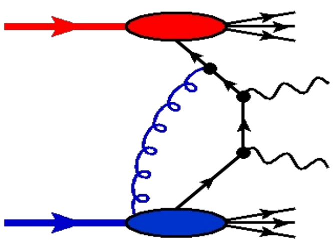




Wilson line in diphoton production:



+



+crossed

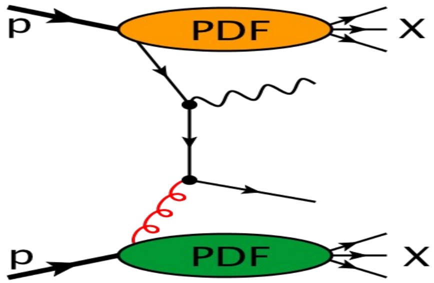
Check for A^+, $A_T^i(z^- = -\infty)$

Diagrams topologically different to DY, *but* cancellations between diagrams

$$\mathcal{W}^{\gamma\gamma}[0;z]\Big|_{z^+=0} = 1 - ig\int_0^{-\infty} d\lambda\, A^+(\lambda n) - ig\int_{0_T}^{z_T} d\vec{y}_T\cdot\vec{A}_T(-\infty,0,\vec{y}_T) - ig\int_{-\infty}^{0} d\lambda\, A^+(\lambda n + z_T) + \mathcal{O}(g^2) = \mathcal{W}^{DY}[0;z]\Big|_{z^+=0}$$

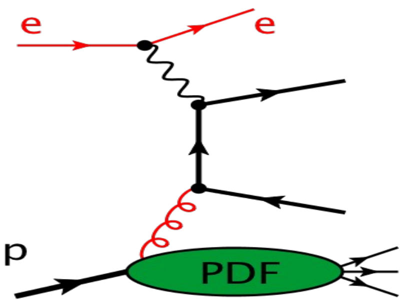
Gluon TMDs in photon pair production

Gluon TMDs in pp-collisions
with colored final state:



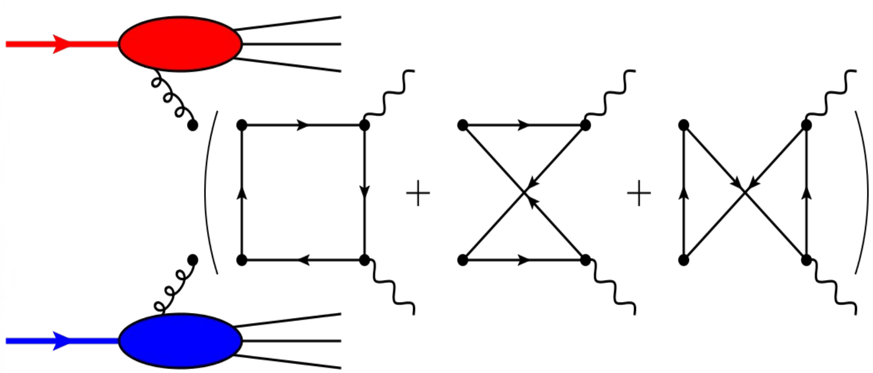
TMD-Factorization (?)

Gluon TMDs in Heavy-quark
production in ep-collisions:



Wait for EIC

Feature of photon pair production → direct sensitivity to gluon TMDs at O($_s^{2}$)

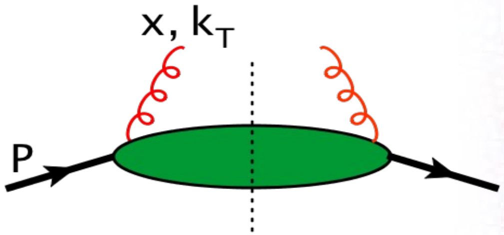


- No colored final state
- Box diagrams finite
- Potentially large gluon distributions
- New Observables, e.g. Cos(4ϕ)

Gluon TMDs

Gluon TMD Correlator:

$$\Gamma_{\mu\nu;\lambda\eta}(x,\vec{k}_T) = \frac{1}{xP^+}\int \frac{dz^- d^2z_T}{(2\pi)^2}\, \mathrm{e}^{ik\cdot z}\langle P,S|\, F^{\alpha}_{\mu\nu}(0)\, \mathcal{W}^{\alpha\beta}[0\,;\,z]\, F^{\beta}_{\lambda\eta}(z)\,|P,S\rangle\Big|_{z^+=0}$$



$\Gamma^{[T-even]}(x,\vec{k}_T)$			$\Gamma^{[T-odd]}(x,\vec{k}_T)$	
		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 $h_{1T}^{\perp,g}$

- Linearly polarized gluons ("Boer-Mulders")
  $\rightarrow$ T-even
- Unpolarized gluons in transv. pol. Proton
  $\rightarrow$ gluonic Sivers Function
- Gluonic Transversity / Pretzelosity / Wormgear
  $\rightarrow$ T-odd
- No chirality
- Two collinear limits

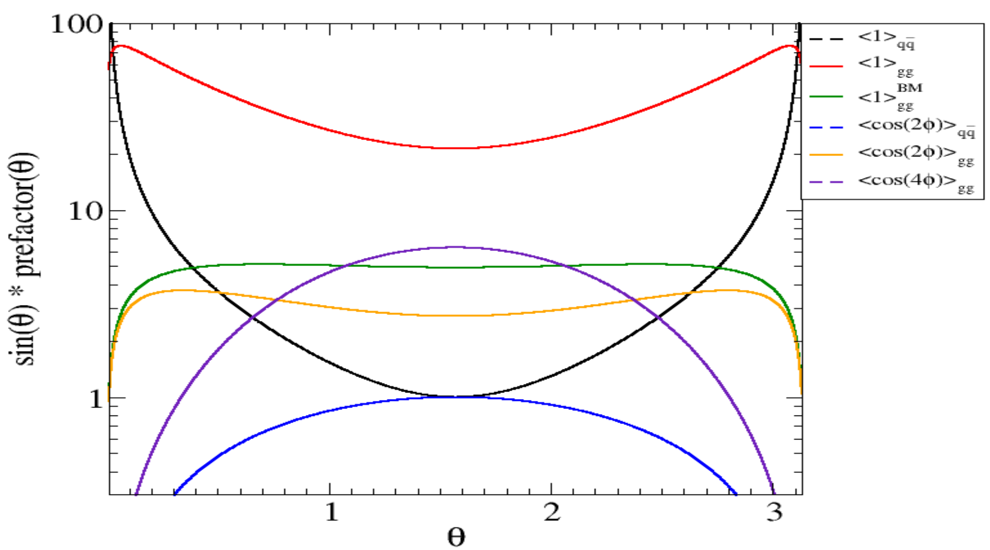
Unpolarized Cross Section

Six structures for the unpolarized cross section ($q_T << Q$)

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

$$+\left(\frac{\alpha_s}{2\pi}\right)^2\Big(\mathcal{F}_1[f_1^g \otimes f_1^g] + \mathcal{F}_2[h_1^{\perp g} \otimes h_1^{\perp g}] + \cos(2\phi)\mathcal{F}_3[h_1^{\perp g} \otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi)\mathcal{F}_4[h_1^{\perp g} \otimes h_1^{\perp g}]\Big)$$

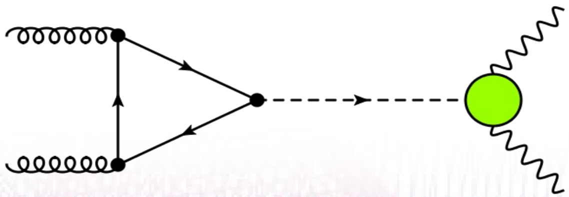
$\mathcal{F}_i$: non-trivial functions of sin(θ) and cos(θ) (Logarithms)



- $q\bar{q}$ singular for θ → 0, π
  → p_T (or θ)-cuts for each photon
- cos(4ϕ) induced by gluon BM- functions,
  → no corresponding quark / DY term.
- powerful in combination with DY
  → even gluon TMD f_1 unknown.
- cos(2ϕ) determines sign of gluon BM-function.
- Same angular structure found in collinear resummation formulas for higher qT.
  (Balazs et al., Catani & Grazzini)

LHC: Diphotons → main channel for Higgs-Prod.

→ Background process: diphotons via quark-box
→ gluon TMD (unpol., BM) feasible



(Maximal) Gluonic BM-effect at RHIC

Estimates at RHIC ($S^{½}$ = 500 GeV) → Gluon (and Quark!) TMDs unknown at RHIC energy

Saturation of Positivity bounds:

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

Gaussian Ansatz:

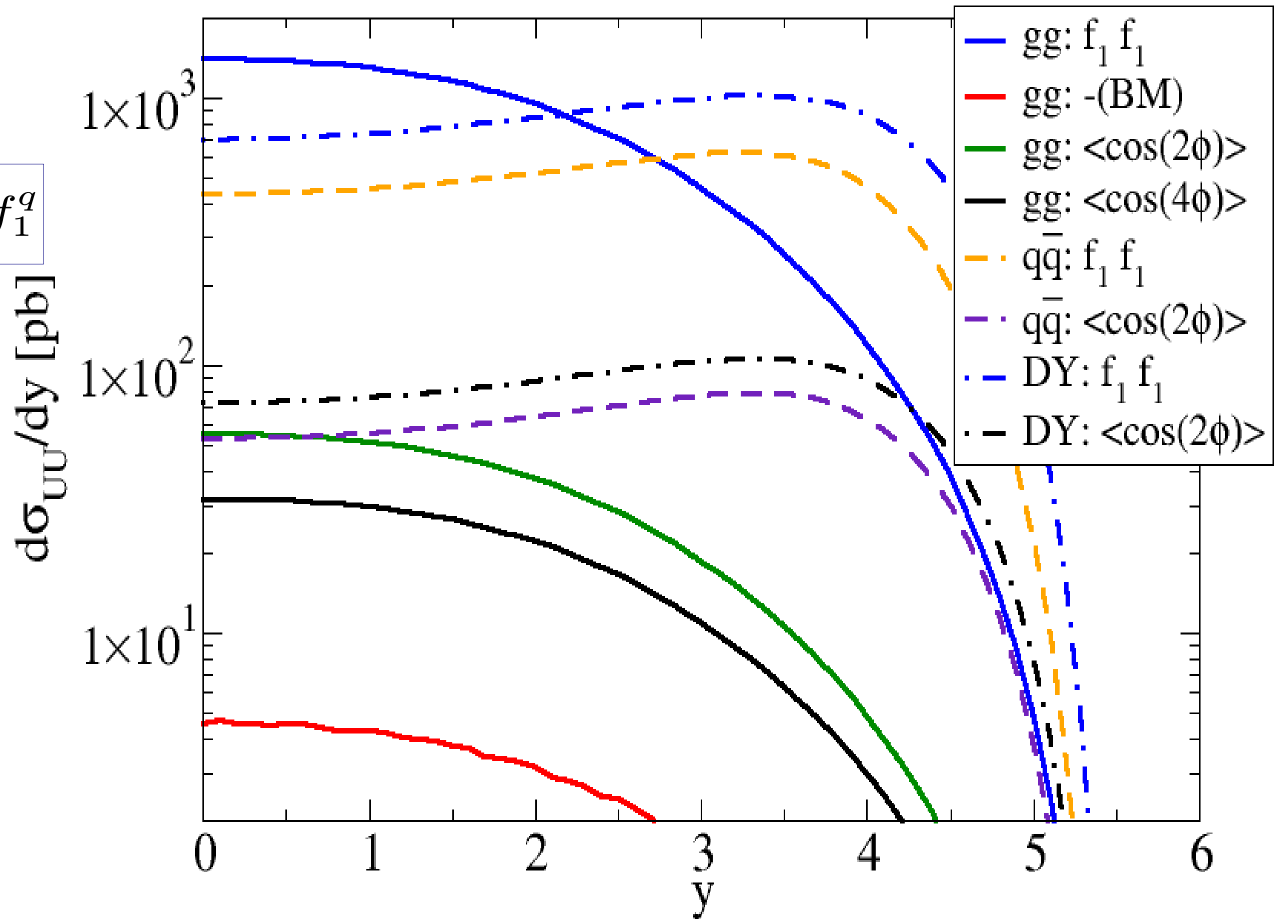
$$f_1^{q/g}(x, k_T^2) = f_1^{q/g}(x)\, e^{-k_T^2/\langle k_{T,q/g}^2 \rangle}$$

Further assumption:

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

P_T-cut for photons:

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



- Gluons at midrapidity, quarks at large rapidity
- BM-contribution to ϕ-indep. CS small
- <cos(4ϕ)> ≤ 1% (depend. on saturation)

Gluonic Sivers-effect at RHIC

Four structures for the ϕ-indep. transv. Single-Spin Asymmetry

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

Positivity bounds:

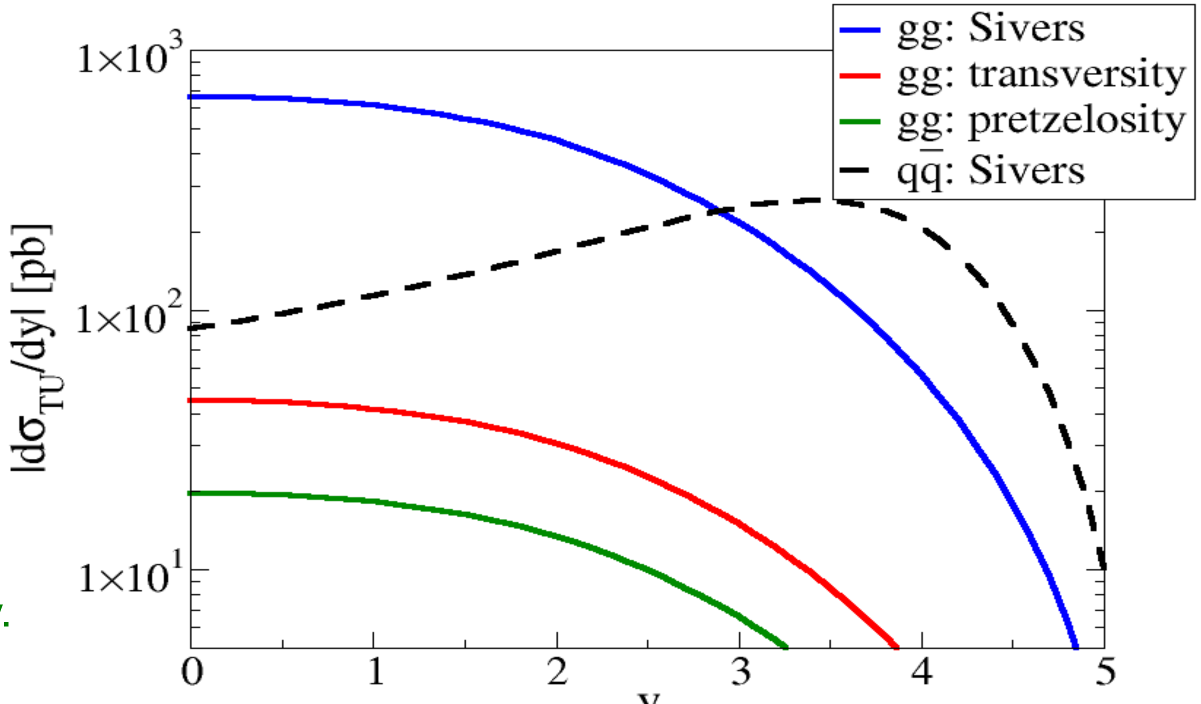
$$|f_{1T}^{\perp,q/g}| \leq \frac{M}{k_T} f_1^{q/g}$$

$$|h_1^g| \leq \frac{M}{k_T} f_1^g \qquad |h_{1T}^{\perp,g}| \leq \frac{2M^3}{k_T^3} f_1^g$$

Flavor cancellation:

$$f_{1T}^{\perp,u} \sim -f_{1T}^{\perp,d}$$

→ pos. pound given by u-quark only.



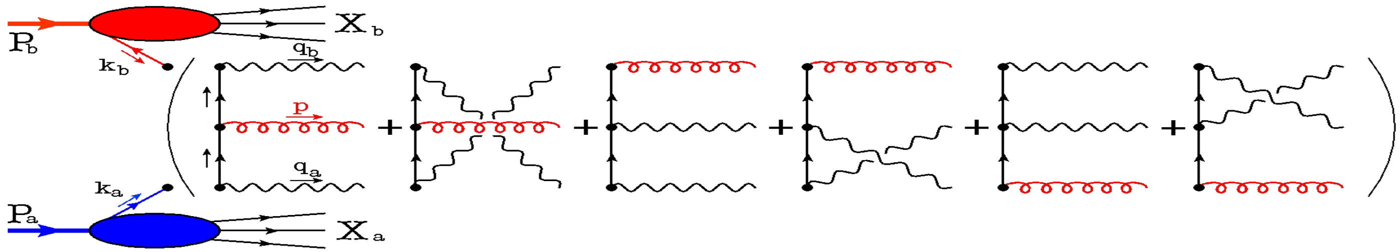
- Sign of Sivers function not predicted by positivity → quark and gluon effects could add.
- Gluonic effects at midrapidity, quark effects at large rapidities.
- Effects by gluon transversity / pretzelosity small.

High - q_T of diphoton production

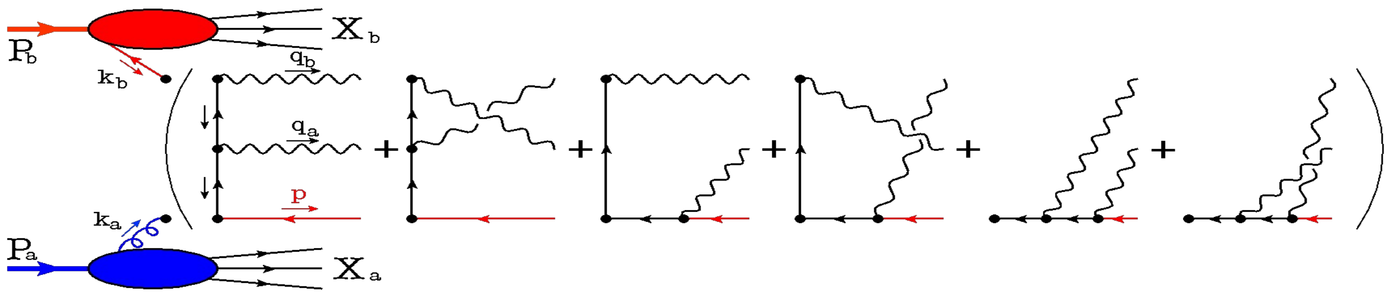
At large $q_T \sim Q \rightarrow$ transverse momentum generated by gluon radiation

$\rightarrow$ collinear parton model calculation

quark – antiquark scattering:



quark – gluon scattering:



Diphoton angles enter the partonic cross section in numerator and denominator
$\rightarrow$ All angular depedencies are allowed.

Situation simplifies for smaller $q_T \rightarrow$ Expansion in $1/q_T$

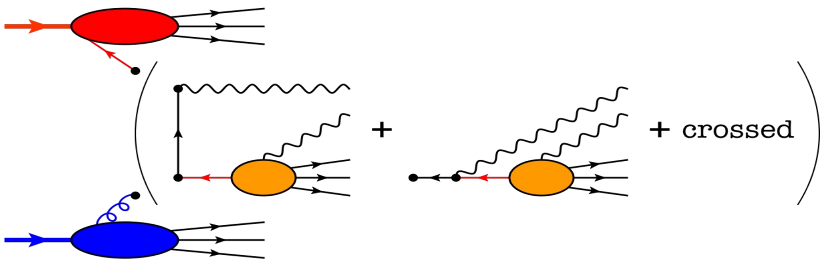
Leading order $(Q^2/q_T^2) \rightarrow$ "TMD-rule" still applies!

$$\sigma^{DP} = \frac{2}{\sin^2\theta}\sigma^{DY}\left(e_q \rightarrow e_q^2\right) + \mathcal{O}(1/q_T)$$

Higher orders $\rightarrow$ "TMD-rule" broken, collinear divergences

Isolation of direct photons

Hide collinear divergence in photon fragmentation function:



- Potentially endangers TMD-factorization
- Photon FF unknown

Circumvent the problem → Isolation [Frixione PLB 429,369; Frixione, Vogelsang NPB 568, 60]

Experimental necessity → diphotons from π°-decays

Define "cone" in rapidity – azimuthal angle space:

$$\mathcal{C}_\gamma(R_0) \equiv \left\{ (\eta,\phi) \,|\, \sqrt{(\eta-\eta_\gamma)^2 + (\phi-\phi_\gamma)^2} \leq R_0 \right\}$$

1. "Traditional" Criterium: allow certain percentage of hadronic energy inside the cone

$$E_T(R_0) \leq \epsilon q_{T\gamma}$$

- Boost-invariant criterium.
- Infra-red safe.
- Allows certain contribution from fragmentation photons.

2. "Improved" Criterium: dynamically generated cone $R < R_0$

$$E_T(R) \leq \epsilon_\gamma \, q_{T\gamma} \, f(R)$$

$$\lim_{R\to 0} f(R) = 0$$

- Boost-invariant criterium.
- Infra-red safe.
- Cuts out *all* fragmentation photons.
- Experimentally harder→ needs high resolution in η and ϕ.

Summary:

- TMD-factorization at low q_T of the photon pair production cross section:
  $q\bar{q}$-contribution: similar to Drell-Yan, gg-contribution: box diagrams
- Gluon and quark contribrution of comparable size at RHIC
- Estimates: Gluon Boer-Mulders may be feasible in a cos(4ϕ)-modulation, also at LHC
- Gluonic Sivers effect may be sizeable in photon pair production.
- p_T-cuts / Isolation needed.
- DY and photon pair rate of comparable size
  → combination of both processes → DY: quark TMDs → Photon pair: gluon TMDs
- Outlook: Project out other gluon TMDs, find optimal Observable for each gluon TMD.