The gluonic Boer-Mulders effect

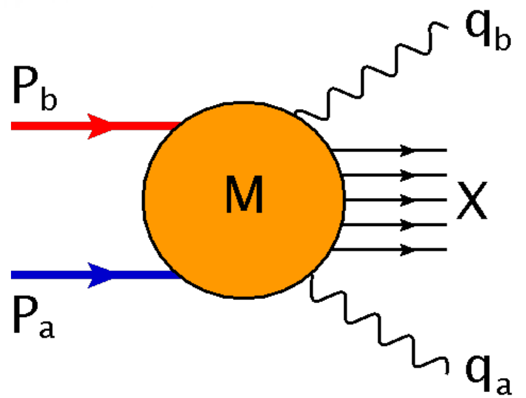
Marc Schlegel

Institute for Theoretical Physics
University of Tuebingen

in collaboration with Werner Vogelsang

"GaryFest 2010", JLab, October 28, 2010

Diphoton production



Two highly energetic real photons produced with

$$q \equiv q_a + q_b$$

$$\frac{d\sigma}{d^4 q_a\, d^4 q_b} = \frac{d\sigma}{d^4 q\, d^4 q_a} \propto \frac{\delta^+(q_a^2)\delta^+((q-q_a)^2)}{2\times 4F} \sum_X |M|^2 \delta^{(4)}(P_a + P_b - q - P_X)$$

Convenient choice: Diphoton rest frame → **Collins-Soper frame**

Photon angles:

$$d^4 q_a \to d\Omega = d\phi\, d\cos\theta$$

Diff. CS including angular dependences: $\frac{d^6\sigma}{d^4 q\, d\Omega} = 2\frac{d^6\sigma}{dy\, dQ^2\, d^2\vec{q}_T d\Omega}$

Unfortunately: No separation into ***hadronic – photonic*** parts possible!
→ *all* angular modulations are allowed, in principle.

$$\frac{d^6\sigma}{dy\, dQ^2\, d^2\vec{q}_T\, d\Omega_a} = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} C_{lm}(y, Q^2, q_T^2)\, Y_{lm}(\Omega_a)$$

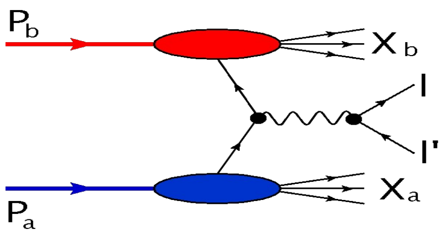
$$C_{00} = \frac{d^4\sigma}{dy\, dQ^2\, d^2 q_T}\,, \ldots$$

However, we can calculate the cross section in the parton model.

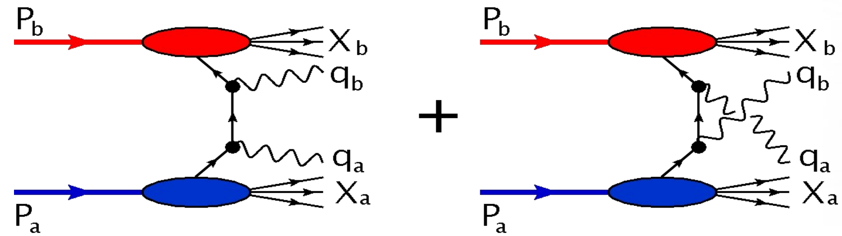
TMD tree-level formalism

Parton model tree-level at $O(\alpha_s^{\,0})$:

Drell-Yan dilepton production:



Diphoton production:



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

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

k_T - correlator:

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

→ can be parameterized in terms of TMDs according to quark / nucleon spin

Main result of the TMD tree-level formalism:

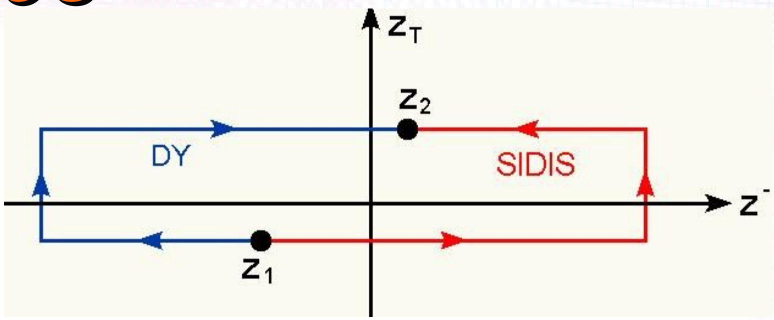
$$\left(\frac{d^6\sigma^{hh\to\gamma\gamma X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q) = \frac{2}{\sin^2\theta}\left(\frac{d\sigma^{hh\to l^+l^- X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q\,|\, e_q \to e_q^2)$$

Numerical estimate for the Sivers effect: Enhancement of event rate by factor 5 - 10

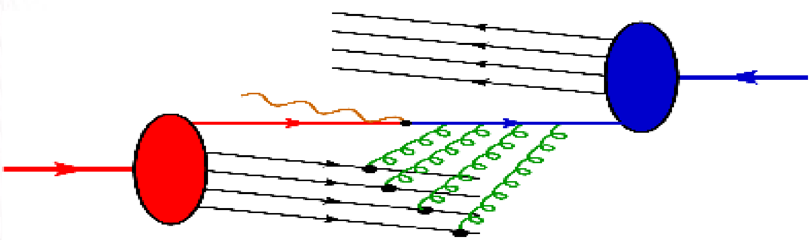
Wilson lines

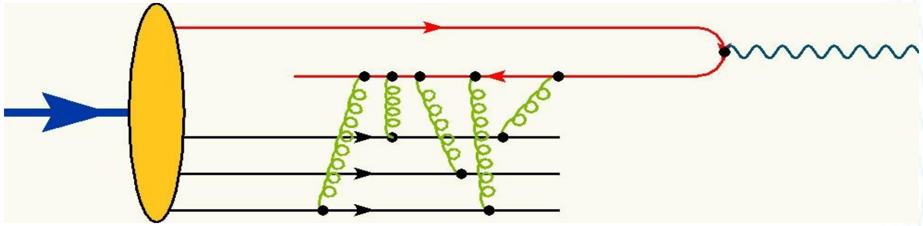
Wilson line process-dependent in DY/SIDIS:

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

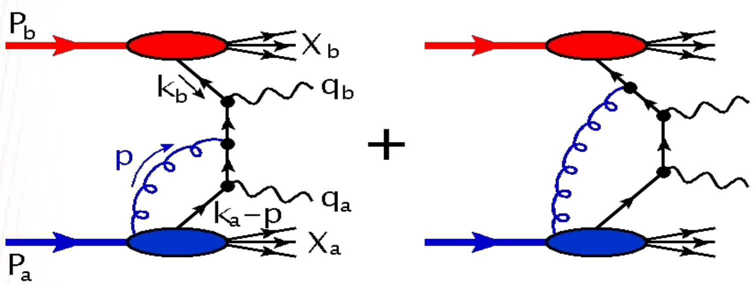


Physics: Initial / Final state interactions





Wilson line in diphoton production:



+crossed

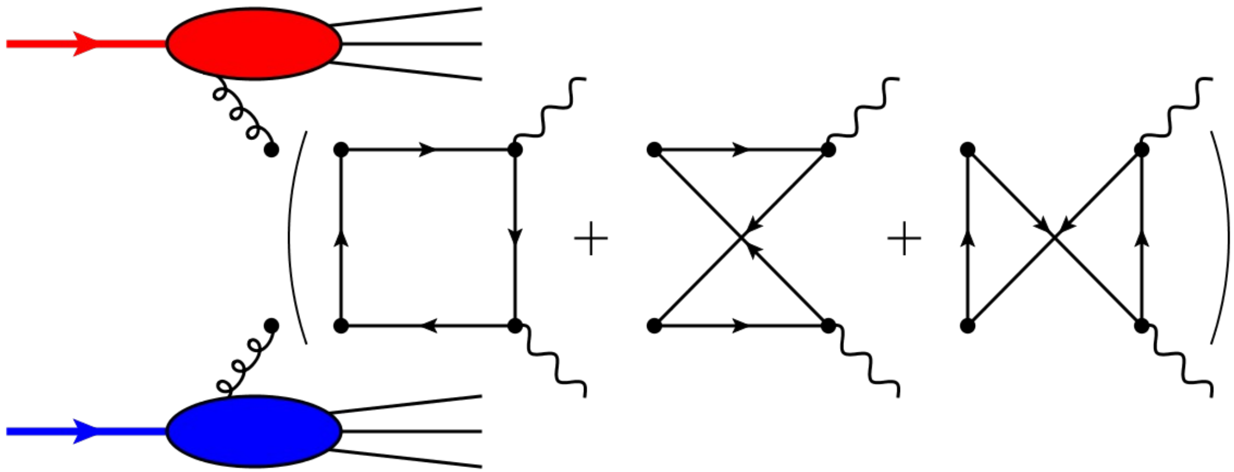
Check for $A^+,\ A_T^i(z^-=-\infty)$

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 diphoton production

Unique feature of diphoton production → direct sensitivity to gluon TMDs at O($_s^2$)



- Current conservation → ”boxes” are IR – and UV-finite → effectively ”tree-level”
- Large gluon distribution at smaller x compensates $_s^2$ suppression → competing process to quark – antiquark generated diphotons
- Polarized gluon TMDs at smaller x → possible contributions feasible at RHIC
- Interaction of two gluons generates new azimuthal asymmetries that are absent for quark – antiquark scattering → e.g., cos(4ϕ) asymmetry in unpol. scattering

Gluon TMD Correlator:

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

Gluon TMDs:

unpolarized hadron:

$$\Gamma_U^{+i;+j}(x,\vec{k}_T) = \frac{\delta^{ij}}{2}\, f_1^g(x,\vec{k}_T^2) + \frac{k_T^i k_T^j - \frac{1}{2}\vec{k}_T^2\delta^{ij}}{2M^2}\, h_1^{\perp g}(x,\vec{k}_T^2)$$

long. pol. hadron:

$$\Gamma_L^{+i;+j}(x,\vec{k}_T) = S_L\frac{i\epsilon_T^{ij}}{2}\, g_1^g(x,\vec{k}_T^2) + S_L\frac{k_T^i\epsilon_T^{jk}k_T^k + (i\leftrightarrow j)}{4M^2}\, h_{1L}^{\perp g}(x,\vec{k}_T^2)$$

transv. pol. hadron:

$$\Gamma_T^{+i;+j}(x,\vec{k}_T) = -\frac{\delta^{ij}}{2}\frac{k_T\times S_T}{M}\, f_{1T}^{\perp g}(x,\vec{k}_T^2) + \frac{i\epsilon_T^{ij}}{2}\frac{\vec{k}_T\cdot\vec{S}_T}{M}\, g_{1T}^{\perp g}(x,\vec{k}_T^2)$$

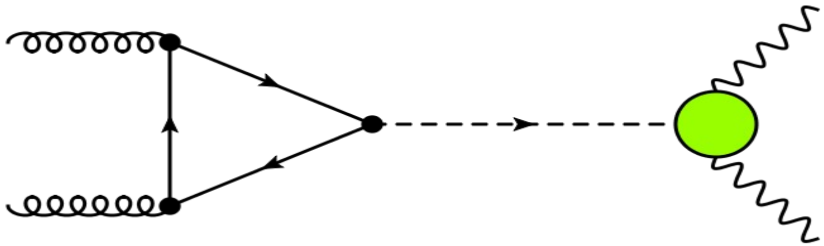
$$+\frac{\epsilon_T^{ik}\left(S_T^j k_T^k + k_T^j S_T^k\right) + (i\to j)}{8M}\, h_{1T}^g(x,\vec{k}_T^2) + \frac{k_T^i\epsilon_T^{jk}k_T^k + (i\leftrightarrow j)}{4M^2}\frac{\vec{k}_T\cdot\vec{S}_T}{M}\, h_{1T}^{\perp g}(x,\vec{k}_T^2)$$

	$\Phi^{[even]}(x,p_T)$		$\Phi^{[odd]}(x,p_T)$	
	even	odd	even	odd
U	f_1			$h_1^{\perp}$
L	g_{1L}	$h_{1L}^{\perp}$		
T	g_{1T}	h_{1T} $h_{1T}^{\perp}$	$f_{1T}^{\perp}$	

	$\Phi^{g[even]}(x,p_T)$		$\Phi^{g[odd]}(x,p_T)$	
		flip		flip
U	f_1^g	$h_1^{\perp g}$		
L	g_{1L}^g			$h_{1L}^{\perp g}$
T	g_{1T}^g		$f_{1T}^{\perp g}$	h_{1T}^g $h_{1T}^{\perp g}$

Gluon TMDs at the LHC:

Diphoton production → important process for Higgs production at LHC



→ Background process: diphoton production via quark-box → gluon TMDs feasible

Unpolarized gluon-gluon cross section (q_T << Q):

$$\frac{\mathrm{d}\sigma_{UU}}{\mathrm{d}^4q\,\mathrm{d}\Omega} \sim \left(\frac{\alpha_s}{2\pi}\right)^2 \Big(\mathcal{F}_1(\theta)[f_1^g \otimes f_1^g] + \cos(2\phi)\mathcal{F}_2(\theta)[h_1^{\perp g} \otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi)\mathcal{F}_3(\theta)[h_1^{\perp g} \otimes h_1^{\perp g}]\Big)$$

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

Factor α_s^2 compensated by (possibly) large unpol. and Boer-Mulders gluon TMDs

cos(4ϕ) induced by gluon Bour-Mulders functions only, no corresponding DY term.

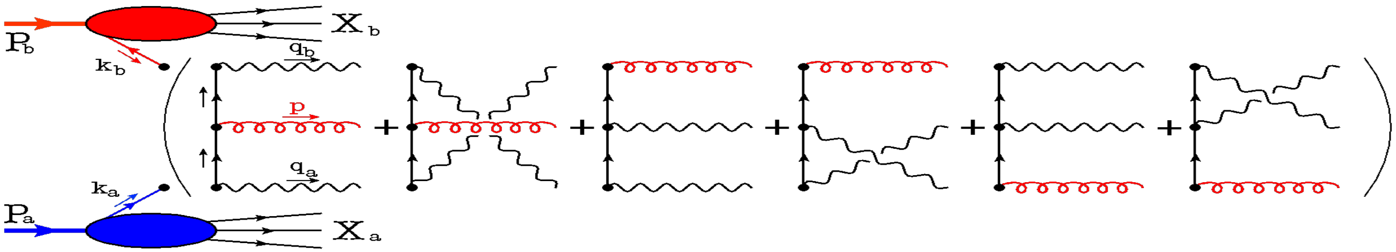
Polarized collisions (RHIC 500GeV): gluon Sivers function, work in progress...

High - q_T of diphoton production

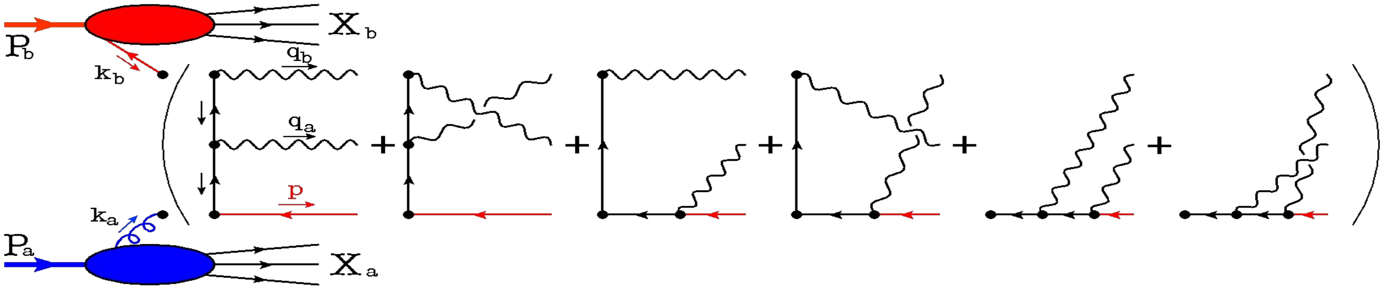
At large $q_T \sim Q \rightarrow$ transverse momentum generated by gluon radiation

$\rightarrow$ collinear parton model calculation

quark – antiquark scattering:



quark – gluon scattering:



However: No model-independent angular decomposition!

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 $1/q_T$

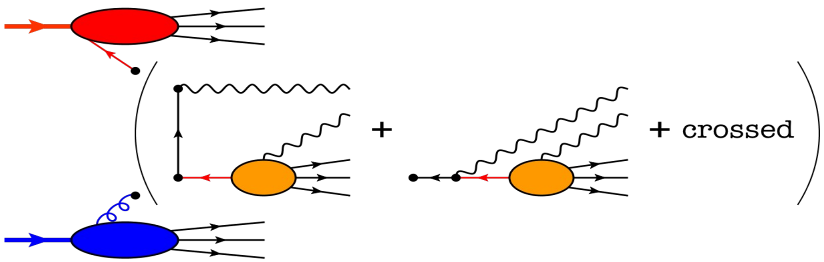
Leading order (Q^2/q_T^2) $\rightarrow$ "TMD-rule" still applies!

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

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^o-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 $R < R_0$

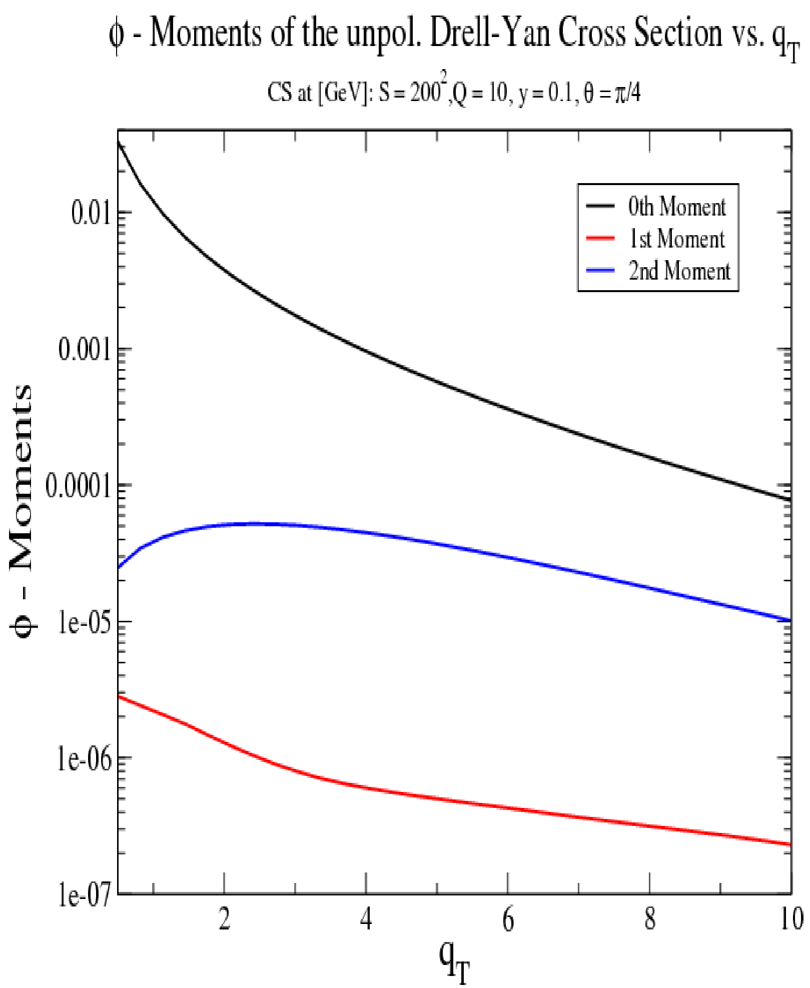
$$E_T(R) \leq \epsilon_\gamma \, q_{T\gamma} \, f(R)$$

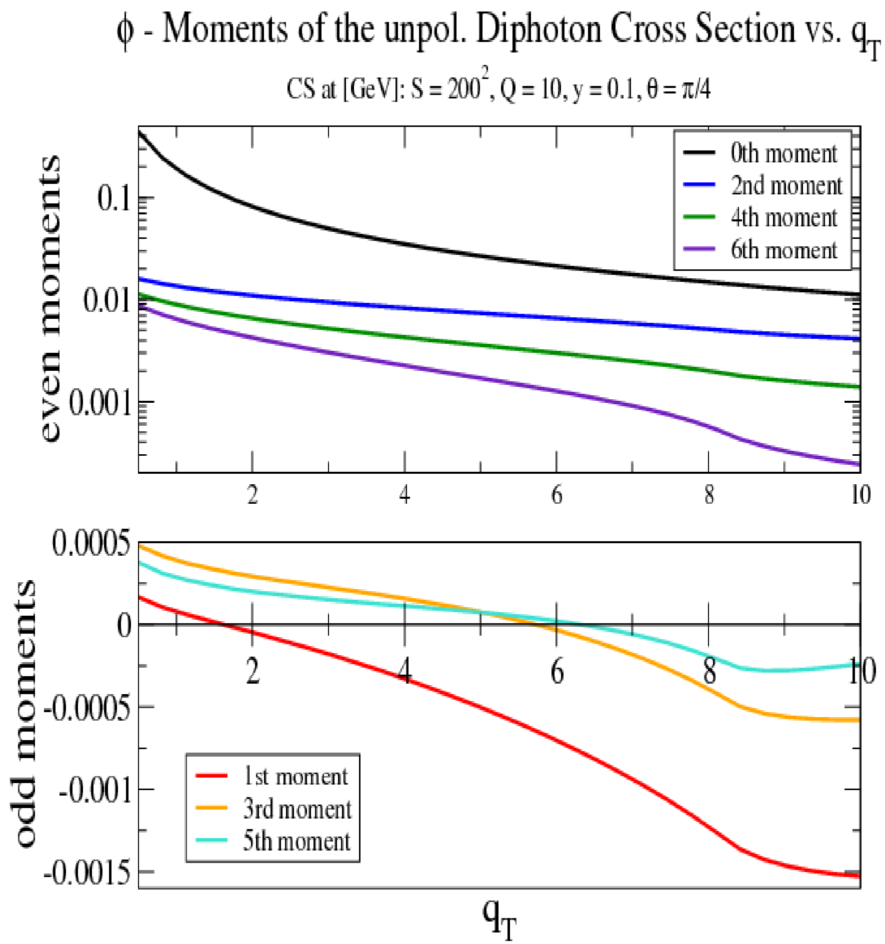
$$\lim_{R\to 0} f(R) = 0$$

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

Define phi moments:

$$\langle \cos(n\phi) \rangle = \int_0^{2\pi} d\phi \cos(n\phi) \frac{d\sigma}{dy\, dQ^2\, d^2 q_T\, d\Omega}$$

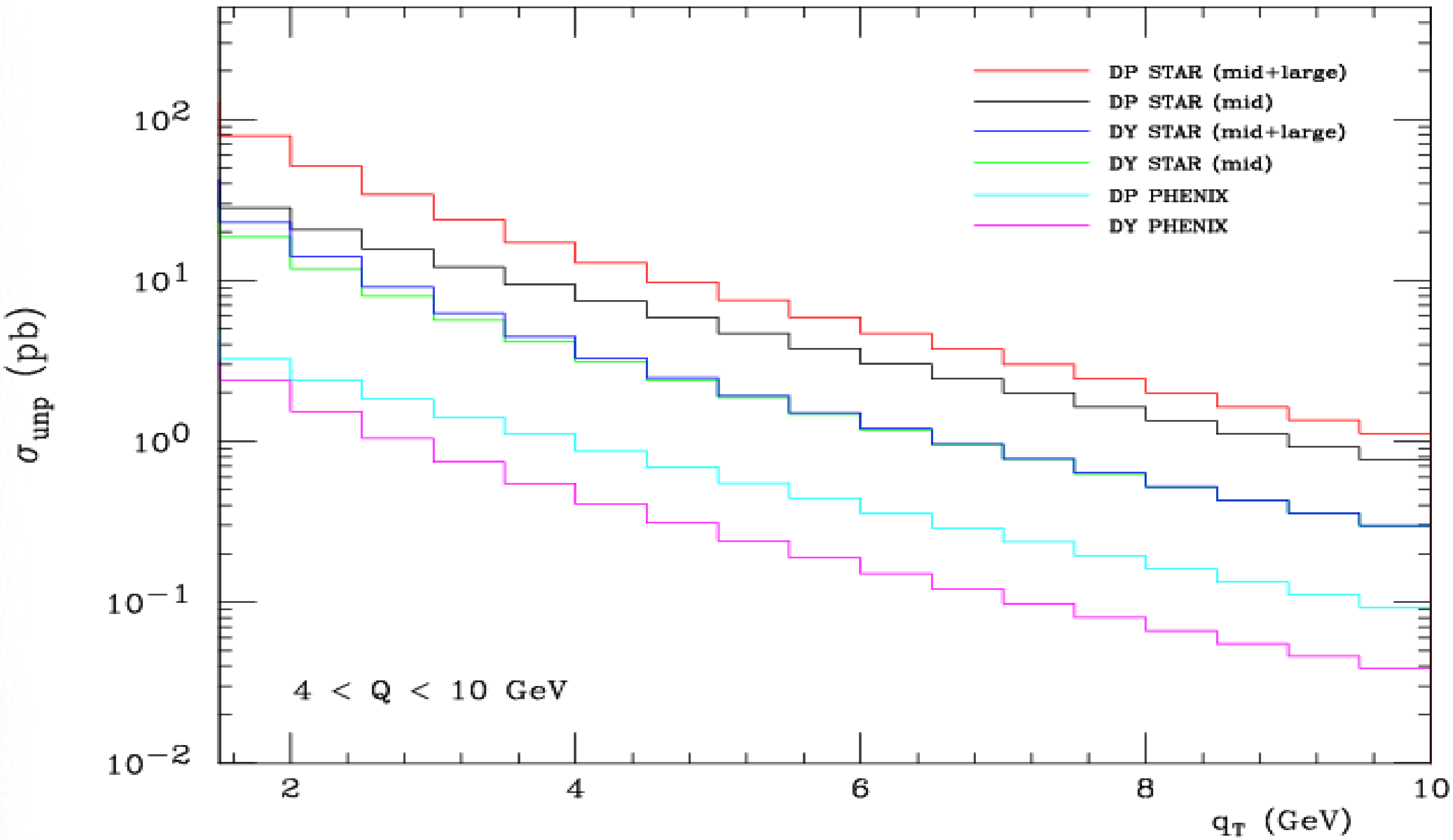




Numerical results

Predictions for the q_T-tail for STAR and PHENIX including isolation:

$$\sigma_{\rm unp} = \int_{\rm cuts} dy\, dQ^2\, dq_T\, d\varphi_q\, d\Omega\, \frac{d\sigma}{dy\, dQ^2\, dq_T\, d\varphi_q\, d\Omega}$$



Also at larger qT → Diphoton production rate about 5 - 10 times larger than Drell-Yan

Summary:

- Drell-Yan cross section can be decomposed model-independently into angular structure function, not possible for photon pair production
- TMD-factorization at low q_T: Photon pair production similar to Drell-Yan
- Sivers effect similar in Photon pair production, but higher production rate → simultaneous measurement
- Photon pair production directly sensitive to Gluon TMDs via quark box → high energy experiments (LHC, RHIC)
- Collinear factorization at larger q_T: all azimuthal modulations possible for photon pair production in contrast to lepton pair production
- Expansion to smaller q_T: Azimuthal behaviour partly recovered → photon fragmentation or Isolation needed.