TMDs and the 3-d Structure of Hadrons in pp-Collisions at CERN

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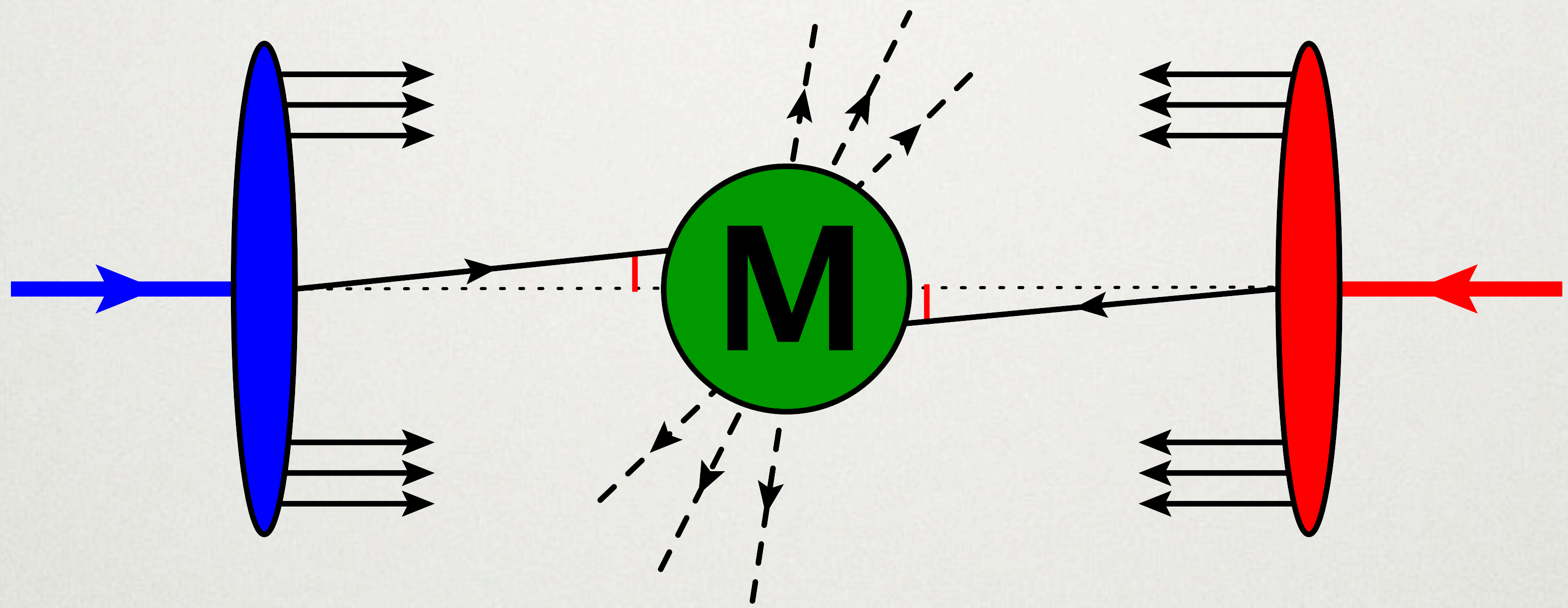
University of Tuebingen

"Drell-Yan Scattering and Structure of Hadrons",
ECT*, Trento, May 24, 2012

Proton-Proton Collisions

physical (factorized) picture

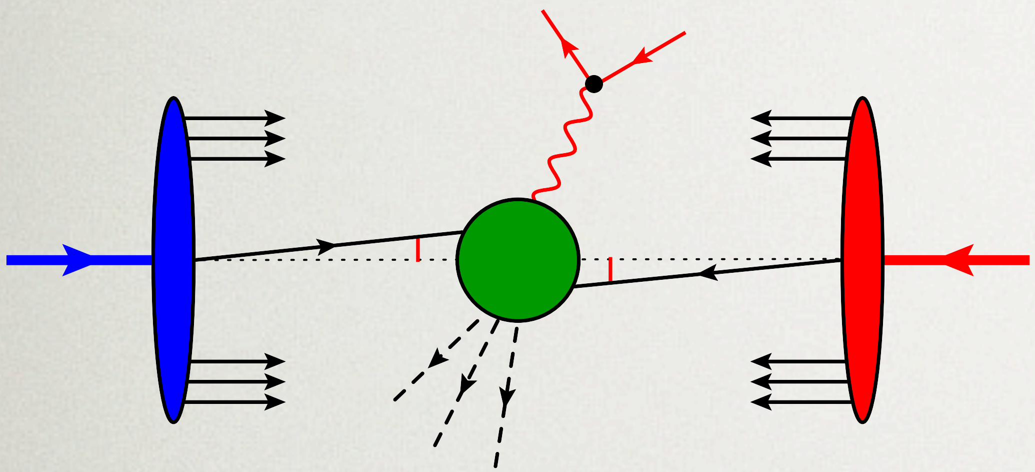


Total momentum of all *detected* final state events:

$q = q_1 + q_2 + q_3 + \ldots \rightarrow y, Q^2, q_T$

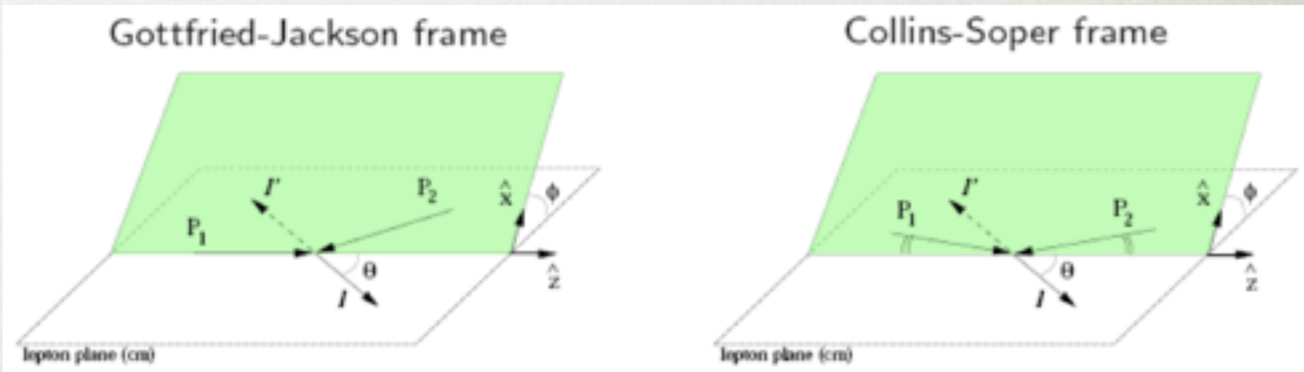
- collinear factorization: all final states! $\frac{d\sigma}{dQ^2}$ $\frac{d\sigma}{dQ^2\, d^2q_T}(\Lambda_{QCD} \ll q_T)$
- TMD factorization: *color-singlet* final states only: $\frac{d\sigma}{dQ^2\, d^2q_T}(\Lambda_{QCD} \sim q_T \ll Q)$

Drell-Yan process



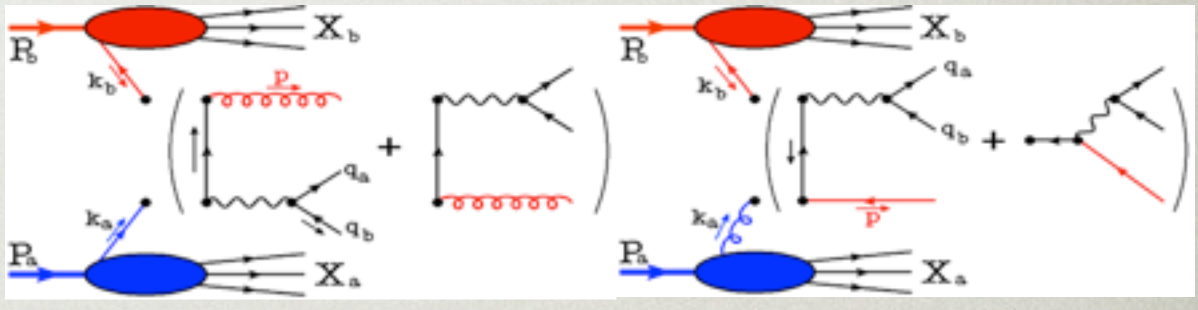
$$\frac{d^6\sigma}{d^4q\, d\Omega} = 2\frac{d^6\sigma}{dy\, dQ^2\, d^2\vec{q}_T d\Omega}$$

Kinematics easy in dilepton rest frame



Collinear factorization

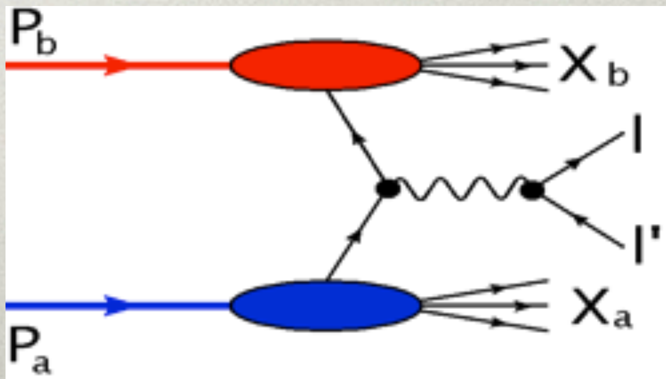
➙ large q_T from undetected parton



TMD factorization

➙ small q_T from intrinsic parton momenta

➙ *only* quark - antiquark interactions!



TMD Factorization (DY)

DY: Separation into *Leptonic* + *Hadronic* Tensor

$$\boxed{\frac{d\sigma}{d^4q\,d\Omega} \propto L_{\mu\nu}W^{\mu\nu}}$$

All-order TMD factorization theorem

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

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

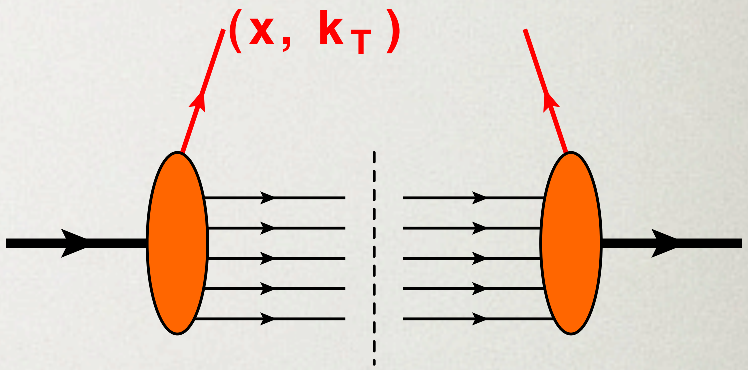
Unpolarized proton ➙ $\boxed{\Phi_U^q(x,\vec{k}_T) = \frac{1}{2}\gamma^- f_1^q(x,\vec{k}_T^2) + \gamma^-\gamma^i\gamma_5\,\frac{\epsilon_T^{ij}k_T^j}{2M}\,h_1^{\perp}(x,\vec{k}_T^2)}$

Boer-Mulders effect ➙ $\boxed{\frac{d\sigma_{UU}}{d^4q\,d\Omega} \propto \mathcal{C}[f_1^q\,f_1^{\bar{q}}] + \cos(2\phi)\mathcal{C}[h_1^{\perp,q}\,h_1^{\perp,\bar{q}}] + \mathcal{O}(\Lambda/Q)}$

(Naive) TMD Definition

Implement "intrinsic" transverse parton momentum k_T

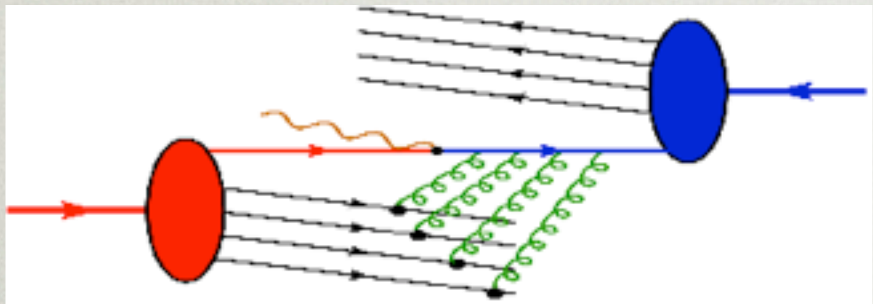
→ opportunity to study different aspects of hadron spin structure (e.g. 3-d momentum structure, spin-orbit correlations, etc.)



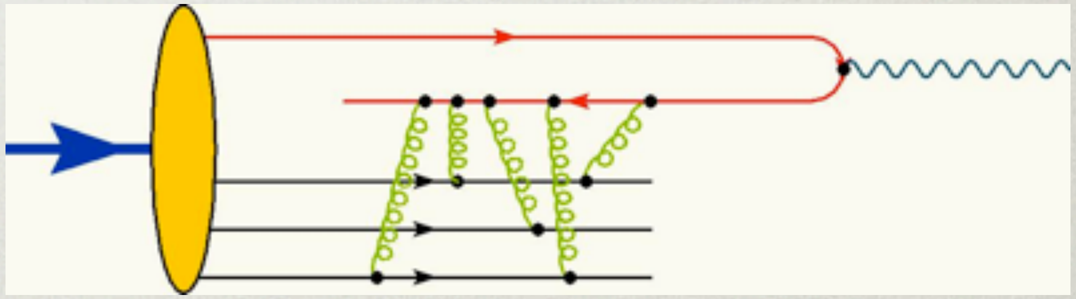
$$\Phi_{ij}(x,\vec{k}_T;S) = \int \frac{dz^- d^2 z_T}{2(2\pi)^3} \, e^{ik\cdot z} \langle P,S| \, \bar{\psi}_j(0) \mathcal{W}_{\mathrm{SIDIS/DY}}[0,z] \, \psi_i(z) \, |P,S\rangle \Big|_{z^+=0}$$

→ Wilson line: Initial / Final State Interactions, process dependence

Initial State Interactions: Drell-Yan



Final State Interactions: SIDIS



→ sign switch of Sivers and Boer-Mulder function "T-odd"

$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$$

$$h_1^{\perp}\Big|_{DIS} = -h_1^{\perp}\Big|_{DY}$$

TMDs and Evolution

[Aybat, Rogers, PRD83, 114042; Collins' "Foundations of pQCD"]

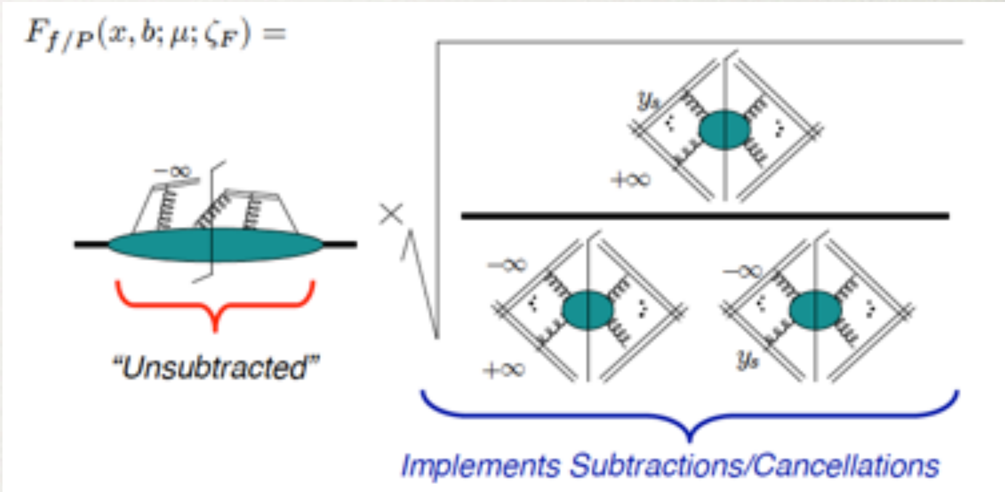
Exact TMD definition beyond tree-level:

1) Wilson lines are off the light cone

→ ξ regulates light cone divergences

→ "unsubtracted " TMD

2) "Soft factors" implemented



$$\boxed{f_1^q(x, \vec{b}_T^2; \mu; \xi) = Z_F Z_2 \lim_{y \to -\infty} \left(f_1^{q,\text{unsub}}(x, \vec{b}_T^2; \mu; y_P - y) \times \sqrt{\frac{S(\vec{b}_T^2; -y, y_s)}{S(\vec{b}_T^2; -y, y) S(\vec{b}_T^2; y_s, y)}} \right)}$$

Evolution equations for ξ (Collins-Soper evolution)

$$\boxed{\frac{\partial \ln f_1^q(x, \vec{b}_T^2; \mu; \xi)}{\partial \ln \sqrt{\xi}} = \frac{1}{2} \frac{\partial}{\partial y_s} \ln \left(\frac{S(\vec{b}_T^2; y_s, -\infty)}{S(\vec{b}_T^2; \infty, y_s)} \right)}$$

anomalous dimensions

$$\boxed{\frac{d \ln f_1^q(x, \vec{b}_T^2; \mu; \xi)}{d \ln \mu} = \gamma_F(g(\mu); \xi/\mu^2)}$$

$$\boxed{\frac{d}{d\mu} \frac{1}{2} \frac{\partial}{\partial y_s} \ln \left(\frac{S(\vec{b}_T^2; y_s, -\infty)}{S(\vec{b}_T^2; \infty, y_s)} \right) = -\gamma_K(g(\mu))}$$

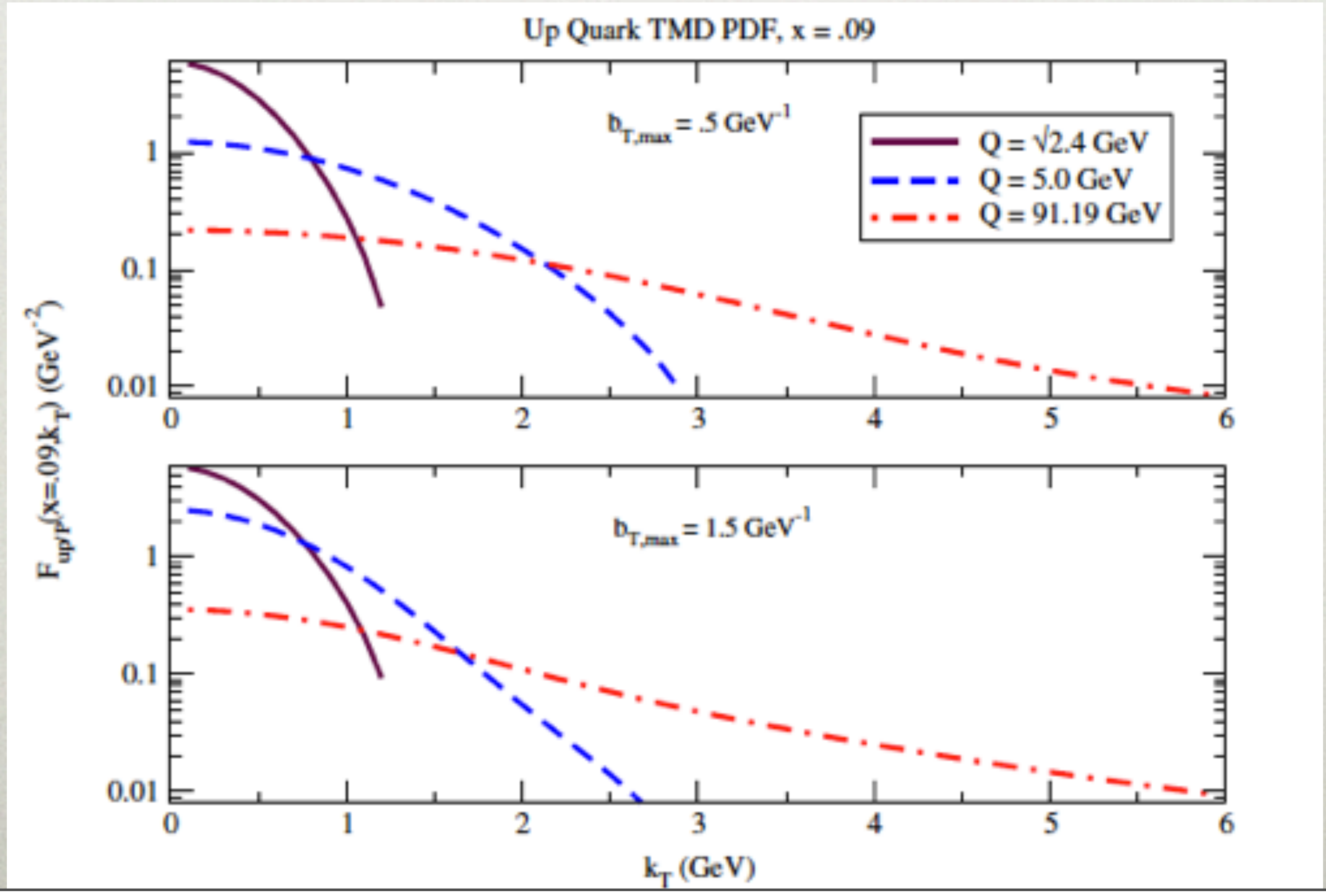
Transverse Momentum Dependence

[Aybat, Rogers, Qiu, Collins; Anselmino, Boglione, ...]

Solution of evolution equation

$$\boxed{f_1^q(x,\vec{b}_T^2;\mu;\xi) = \sum_{q'} \left(\tilde{C}_{qq'} \otimes q(x)\right)\Big|_{\mu\propto 1/b_*} \mathrm{e}^{S_{\mathrm{pert}}(b_*)}\Big|_{\mu\propto 1/b_*} \mathrm{e}^{g_q(x,b_T)+\frac{1}{2}g_K(b_T)\ln\frac{\xi}{\xi_0}}}$$

TMD at large k_T perturbative Sudakov factor   non-perturbative input



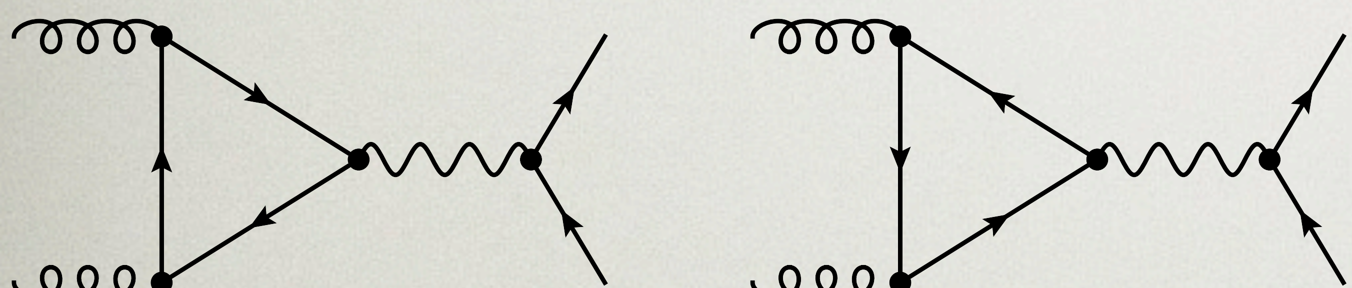
Proton-Proton Collisions beyond DY

Further leptonic final states available for TMD factorization

$$p + p \rightarrow \Big((l\bar{l}),\, (\gamma\gamma),\, (\gamma\, l\bar{l}),\, (l'\bar{l}')(l\bar{l}), \ldots\Big) + X$$

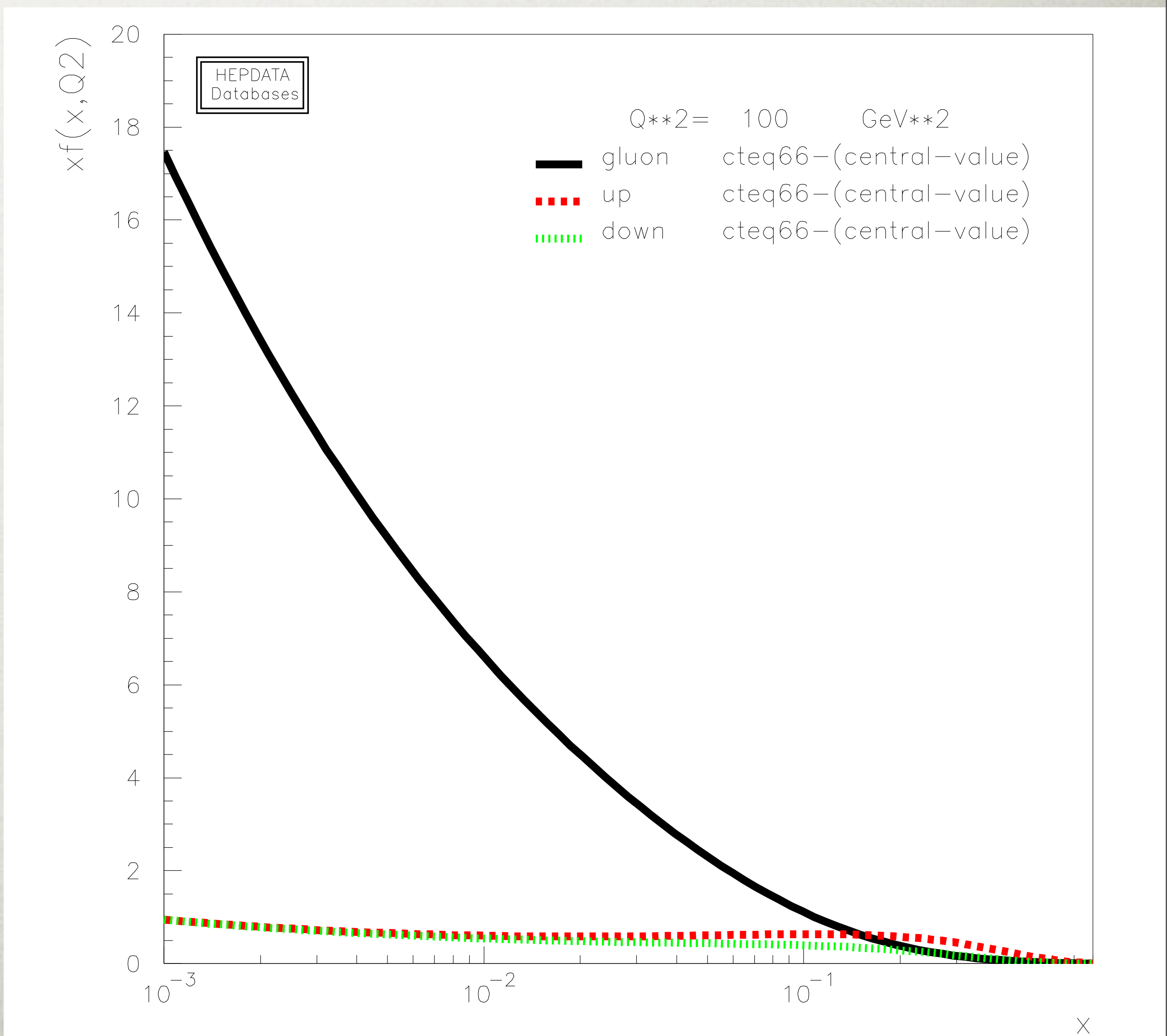
- Gluon-Gluon fusion at NNLO through loops
  ➙ known to contribute in coll. factorization

- No gluon fusion in Drell-Yan (Furry's Theorem)



- Chance to study gluon TMDs at low x

$$x_a\, x_b = \frac{Q^2}{S\,(1 + q_T^2/Q^2)} \sim \Big(\frac{10 - 100\,\mathrm{GeV}}{7000 - 14000\,\mathrm{GeV}}\Big)^2$$

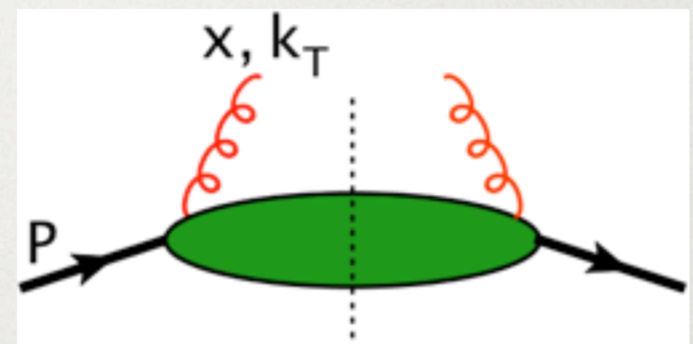


Gluon TMDs

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

$\Gamma^{[T-even]}(x,\vec{k}_T)$			$\Gamma^{[T-odd]}(x,\vec{k}_T)$	
		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 discussed w.r.t. gluon TMDs

Gluon TMDs do not appear in Drell-Yan or SIDIS...

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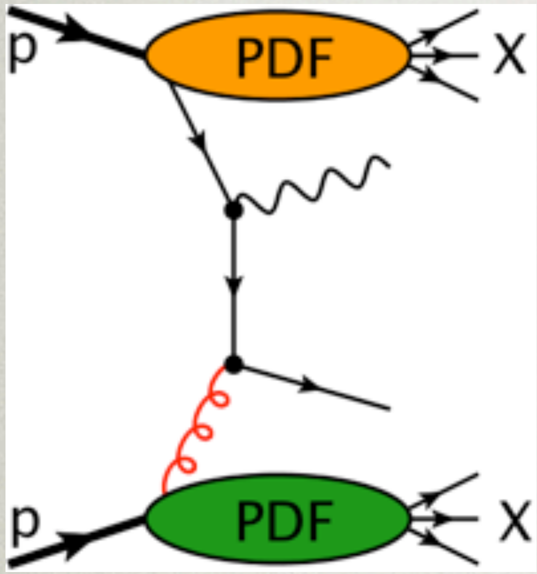

Jet / Hadron production in pp - collisions

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

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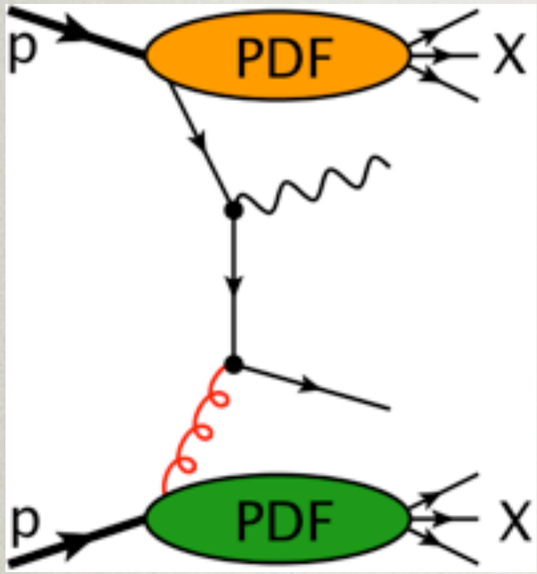

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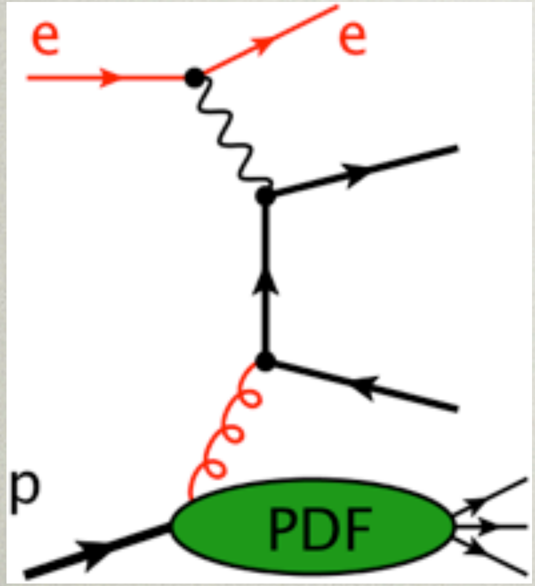


Heavy Quark production in ep - collisions

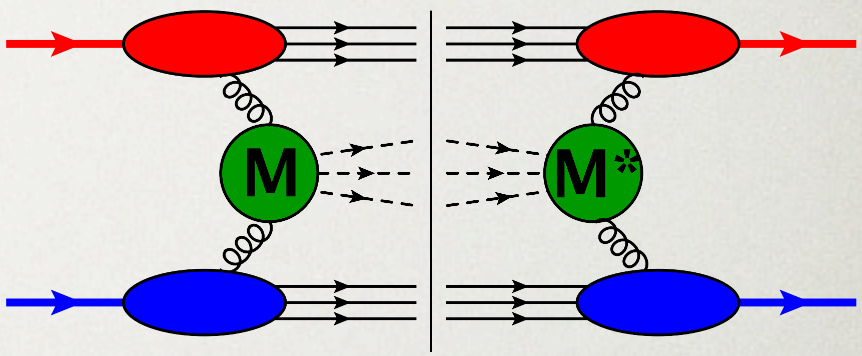
[Boer, Brodsky, Mulders, Pisano, PRL 106, 132001]

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

Gluon - Gluon Interactions

General gluonic TMD expression:

$$\boxed{\frac{d\sigma}{d^4q\, d\Omega \ldots}(q_T \ll Q) \propto \mathcal{C}[\Gamma^{ij}(x_a, \vec{k}_{aT})\, \Gamma^{kl}(x_b, \vec{k}_{bT})] \sum_I \left(\mathcal{M}^{ik;I}(\mathcal{M}^{jl,I})^*\right)}$$



unpolarized proton:

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

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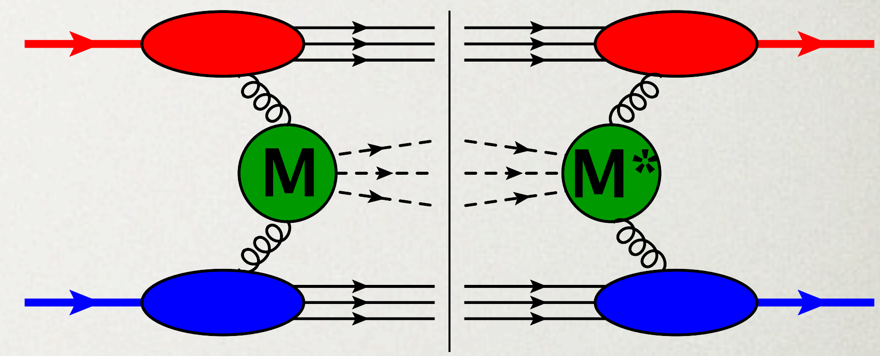

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Calculation of partonic amplitudes
➙ convenient to use gluon polarization vectors
➙ helicity amplitudes

$$\varepsilon_\lambda^\mu(k_a) = (0, 1, i\lambda, 0)/\sqrt{2}$$

$$\delta_T^{\mu\nu} = \sum_\lambda \varepsilon_\lambda^\mu(k_{a/b})(\varepsilon_\lambda^\nu)^*(k_{a/b})$$

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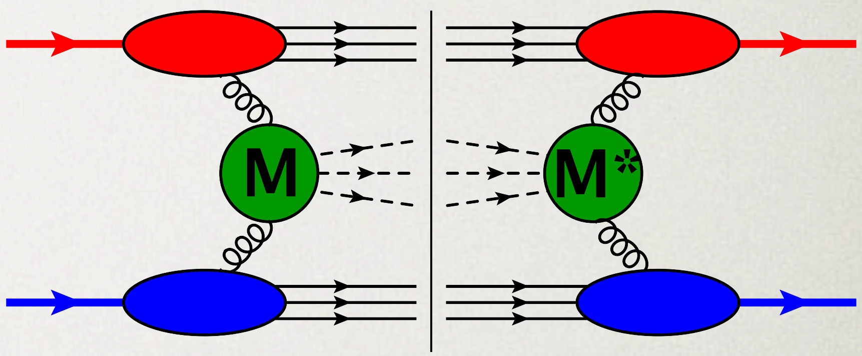

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Helicity correlator:

$$\Gamma_{\lambda_1\lambda_2}(x, \vec{k}_T) \equiv \Gamma^{ij}(x, \vec{k}_T)\,(\varepsilon_{\lambda_1}^i(k))^*\,(\varepsilon_{\lambda_2}^j(k))^* = \frac{1}{2}\left(\delta_{\lambda_1,\lambda_2}\, f_1^g(x, \vec{k}_T^2) + \delta_{\lambda_1,-\lambda_2}\frac{(k_x - i\lambda_1 k_y)^2}{2M^2}\, h_1^{\perp g}(x, \vec{k}_T^2)\right)$$

helicity non-flip

helicity flip

GENERAL GG - STRUCTURES

General TMD cross section in the helicity formalism

$$\frac{d\sigma}{d^4q\, d\Omega \ldots}(q_T \ll Q) \propto \mathcal{C}[\Gamma_{\lambda_a \lambda_{a'}}(x_a, \vec{k}_{aT})\, \Gamma_{\lambda_b \lambda_{b'}}(x_b, \vec{k}_{bT})] \sum_I \left(\mathcal{M}^I_{\lambda_a \lambda_b} (\mathcal{M}^I_{\lambda_{a'}, \lambda_{b'}})^* \right)$$

Decomposition into four structures

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$$\boxed{\mathcal{C}\,[f_1^g\, f_1^g] \left(\sum_I \mathcal{M}^I_{\lambda_a \lambda_b} (\mathcal{M}^I_{\lambda_a \lambda_b})^* \right)} \rightarrow F_1(Q, \Omega, \ldots)$$

→ helicity non-flip, ϕ - independent, survives q_T-integration

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→ helicity non-flip, ϕ - independent, survives q_T-integration

$$\mathcal{C}\left[\frac{(k_{ax}^2 - k_{ay}^2)(k_{bx}^2 - k_{by}^2) + 4 k_{ax} k_{bx} k_{ay} k_{ay}}{16 M^4} h_1^{\perp g}\, h_1^{\perp g} \right] \left(\sum_I \mathcal{M}^I_{\lambda_a \lambda_a} (\mathcal{M}^I_{-\lambda_a - \lambda_a})^* \right) \rightarrow F_2(Q, \Omega, \dots)$$

→ double helicity flip,
ϕ - independent,
vanishes upon q_T-integration

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$$\boxed{\mathcal{C}\left[\frac{(k_{ax}^2 - k_{ay}^2)}{4M^2} h_1^{\perp g}\, f_1^g\right] \left(\sum_I \mathcal{M}^I_{\lambda_a \lambda_b} (\mathcal{M}^I_{-\lambda_a \lambda_b})^*\right)} \rightarrow F_{3,a}(Q, \Omega, \ldots)$$

→ single helicity flip, cos(2ϕ) - mode, weighted q_T-integration

$$\boxed{\mathcal{C}\left[\frac{(k_{bx}^2 - k_{by}^2)}{4M^2} f_1^g\, h_1^{\perp g}\right] \left(\sum_I \mathcal{M}^I_{\lambda_a \lambda_b} (\mathcal{M}^I_{\lambda_a - \lambda_b})^*\right)} \rightarrow F_{3,b}(Q, \Omega, \ldots)$$

→ single helicity flip, cos(2ϕ) - mode, weighted q_T-integration

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$$\frac{d\sigma}{d^4q\, d\Omega \ldots}(q_T \ll Q) \propto \mathcal{C}[\Gamma_{\lambda_a\lambda_{a'}}(x_a, \vec{k}_{aT})\,\Gamma_{\lambda_b\lambda_{b'}}(x_b, \vec{k}_{bT})] \sum_I \left(\mathcal{M}^I_{\lambda_a\lambda_b}(\mathcal{M}^I_{\lambda_{a'},\lambda_{b'}})^*\right)$$

Decomposition into four structures

$$\mathcal{C}\,[f_1^g\, f_1^g] \left(\sum_I \mathcal{M}^I_{\lambda_a\lambda_b}\,(\mathcal{M}^I_{\lambda_a\lambda_b})^*\right) \rightarrow F_1(Q, \Omega, \ldots)$$

→ helicity non-flip, ϕ - independent, survives q_T-integration

$$\mathcal{C}\left[\frac{(k_{ax}^2 - k_{ay}^2)(k_{bx}^2 - k_{by}^2) + 4k_{ax}k_{bx}k_{ay}k_{ay}}{16M^4} h_1^{\perp g}\, h_1^{\perp g}\right] \left(\sum_I \mathcal{M}^I_{\lambda_a\lambda_a}\,(\mathcal{M}^I_{-\lambda_a-\lambda_a})^*\right) \rightarrow F_2(Q, \Omega, \ldots)$$

→ double helicity flip, ϕ - independent, vanishes upon q_T-integration

$$\mathcal{C}\left[\frac{(k_{ax}^2 - k_{ay}^2)}{4M^2} h_1^{\perp g}\, f_1^g\right] \left(\sum_I \mathcal{M}^I_{\lambda_a\lambda_b}\,(\mathcal{M}^I_{-\lambda_a\lambda_b})^*\right) \rightarrow F_{3,a}(Q, \Omega, \ldots)$$

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→ single helicity flip, cos(2ϕ) - mode, weighted q_T-integration

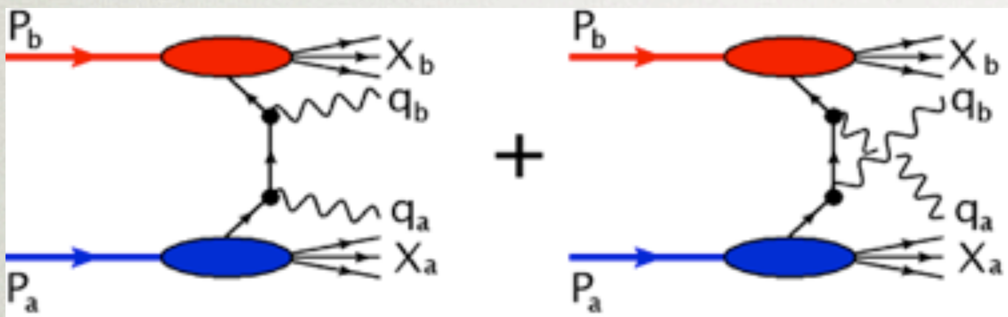
$$\mathcal{C}\left[\frac{(k_{ax}^2 - k_{ay}^2)(k_{bx}^2 - k_{by}^2) - 4k_{ax}k_{bx}k_{ay}k_{ay}}{16M^4} h_1^{\perp g}\, h_1^{\perp g}\right] \left(\sum_I \mathcal{M}^I_{\lambda_a-\lambda_a}\,(\mathcal{M}^I_{-\lambda_a\lambda_a})^*\right) \rightarrow F_4(Q, \Omega, \ldots)$$

→ double helicity flip, cos(4ϕ) - mode , weighted q_T-integration

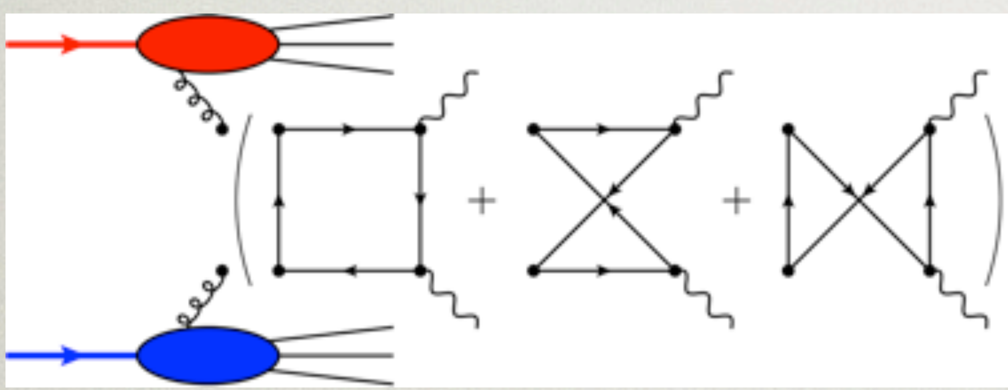
Box diagrams

Diphotons

quark -antiquark interactions



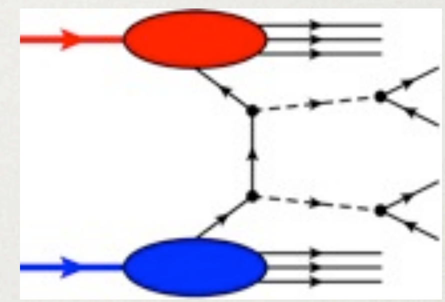
gluon TMDs at $O(\alpha_s^2)$

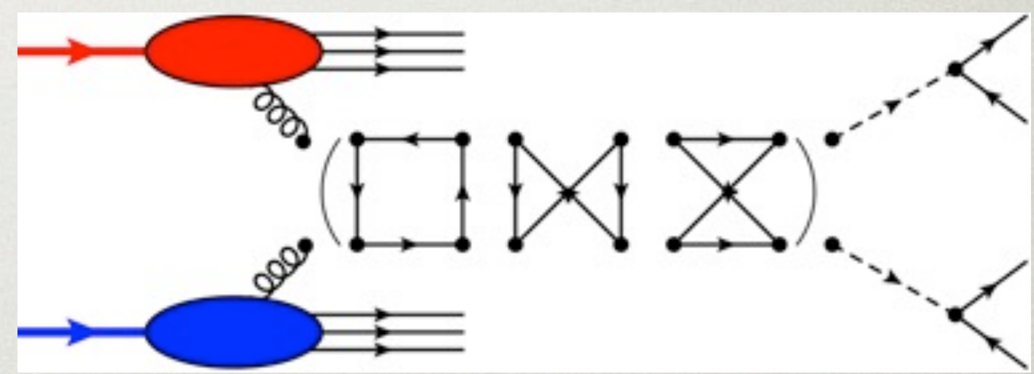


[Qiu, M.S., Vogelsang, PRL 107, 062001 (2011)]

Other leptonic final states:

➙ ZZ, WW, 4l, Zγ, 2lγ





[Boer, den Dunnen, Pisano, MS, Vogelsang, in prep.]

- no colored final state ⇒ TMD factorization ok
- only Initial State Interactions, past-pointing Wilson lines
- gauge invariance ⇒ box finite ⇒ effectively tree-level

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

gluon contributions ➙ absent in DY

$\mathcal{F}_i(\theta)$→ non-trivial functions of cos(θ) and sin(θ) (Logarithms from quark loop)

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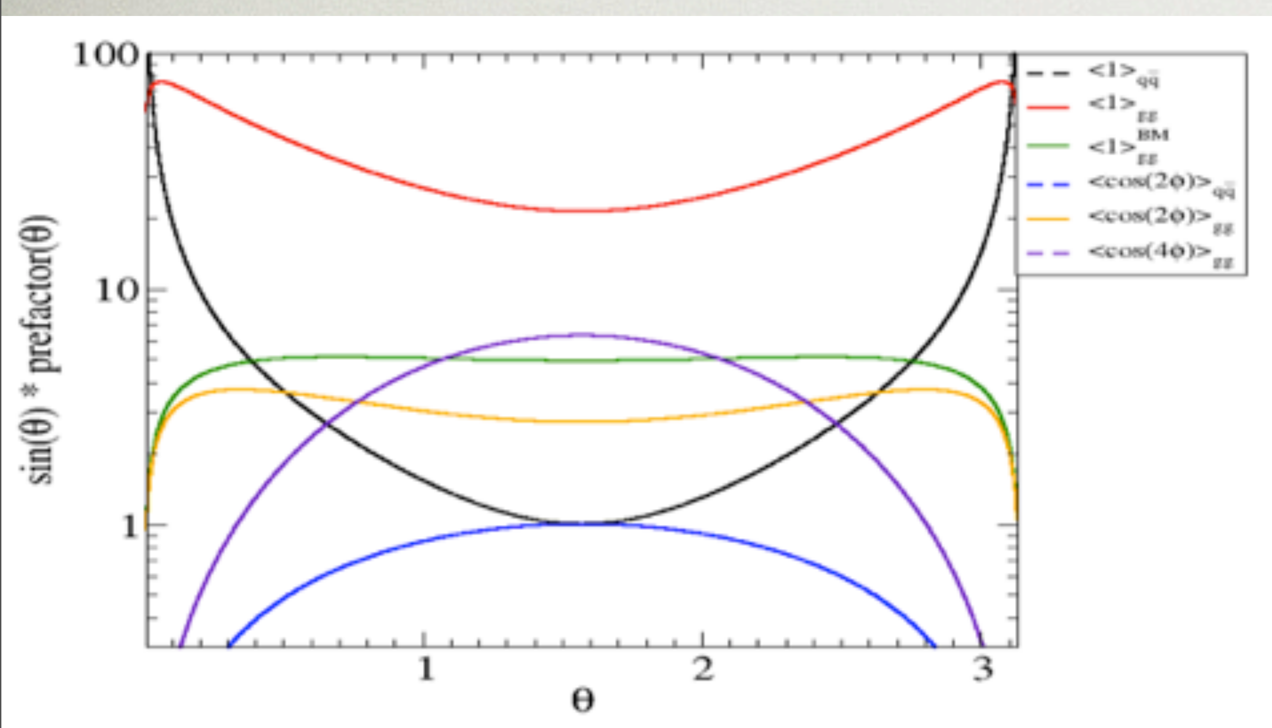


- cos(4ϕ) modulation a pure gluonic effect
- cos(2ϕ) ➙ sign of gluon $h_1^\perp$
- requires p_T & isolation cuts for the photons
- powerful in combination with DY
  ➙ map out quark TMDs in DY → gluon TMDs in γγ

Numerical Estimate

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

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:

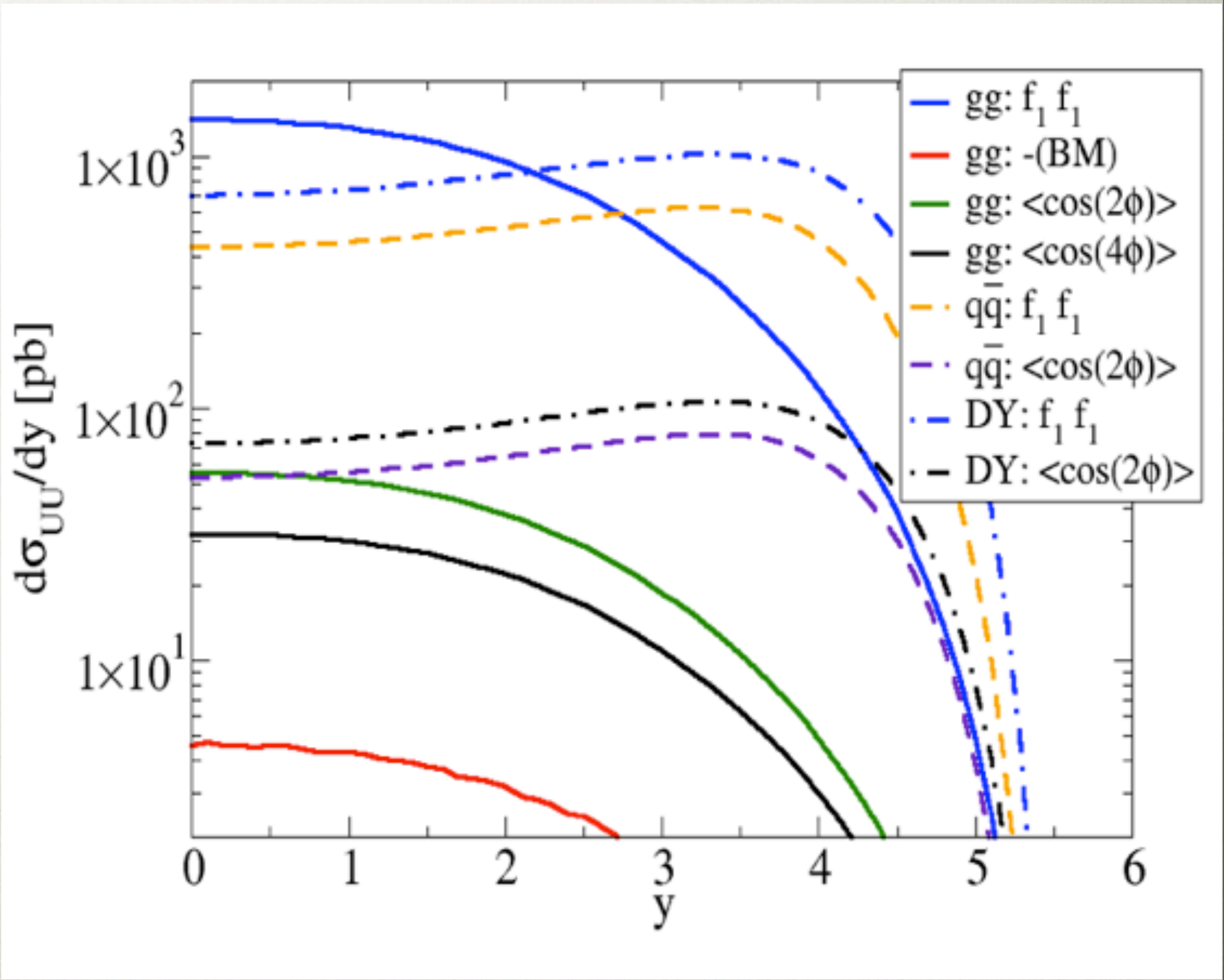
$$f_1^{q/g}(x,k_T^2) = f_1^{q/g}(x)\,\mathrm{e}^{-k_T^2/\langle k_{T,q/g}^2\rangle}$$

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:

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



→ Gluon TMDs feasible at RHIC at mid-rapidity!

Gluon Sivers Effect

(Transverse) Spin dependent photon pair cross section:

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

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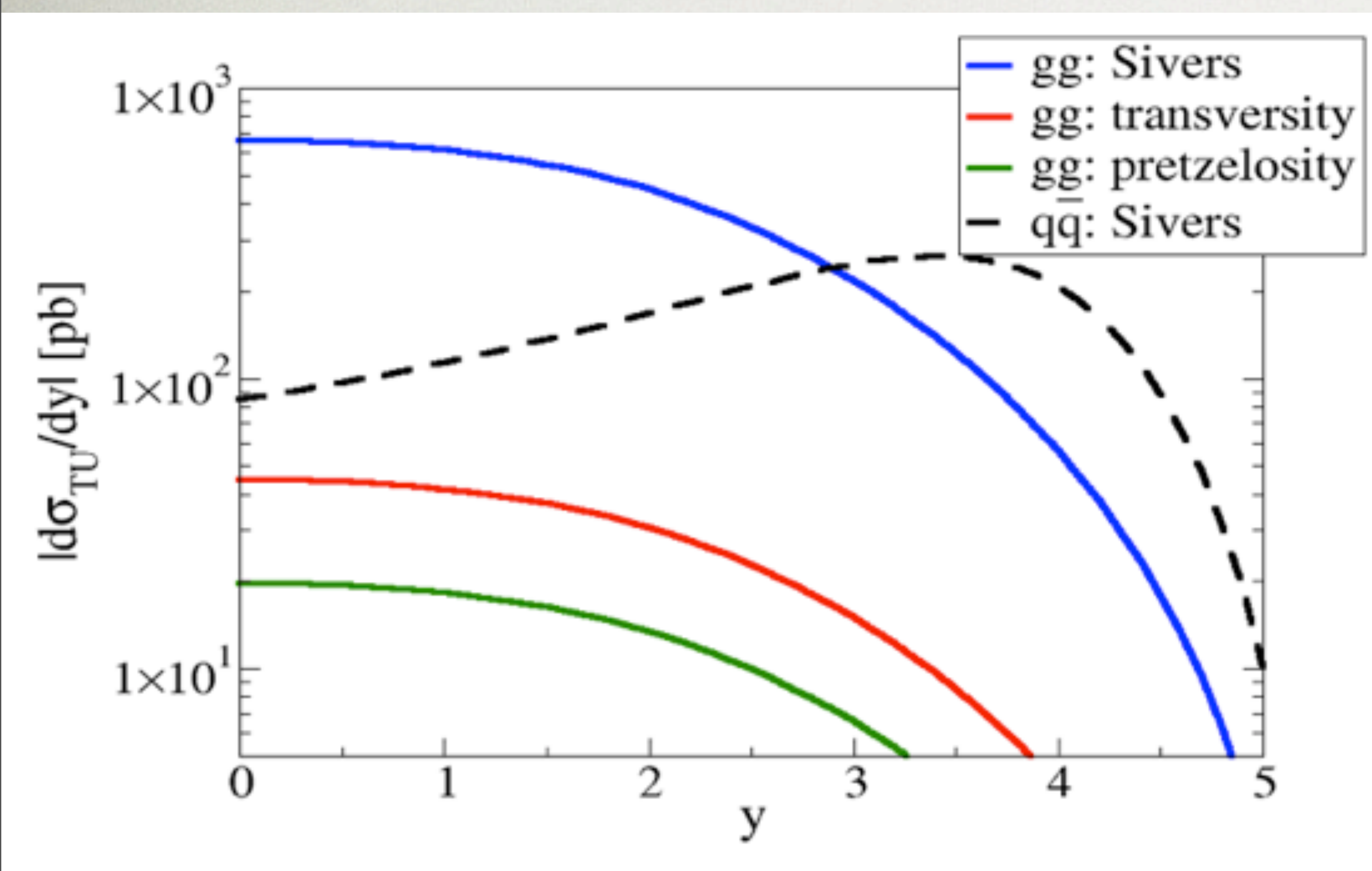
Estimates for RHIC 500 GeV



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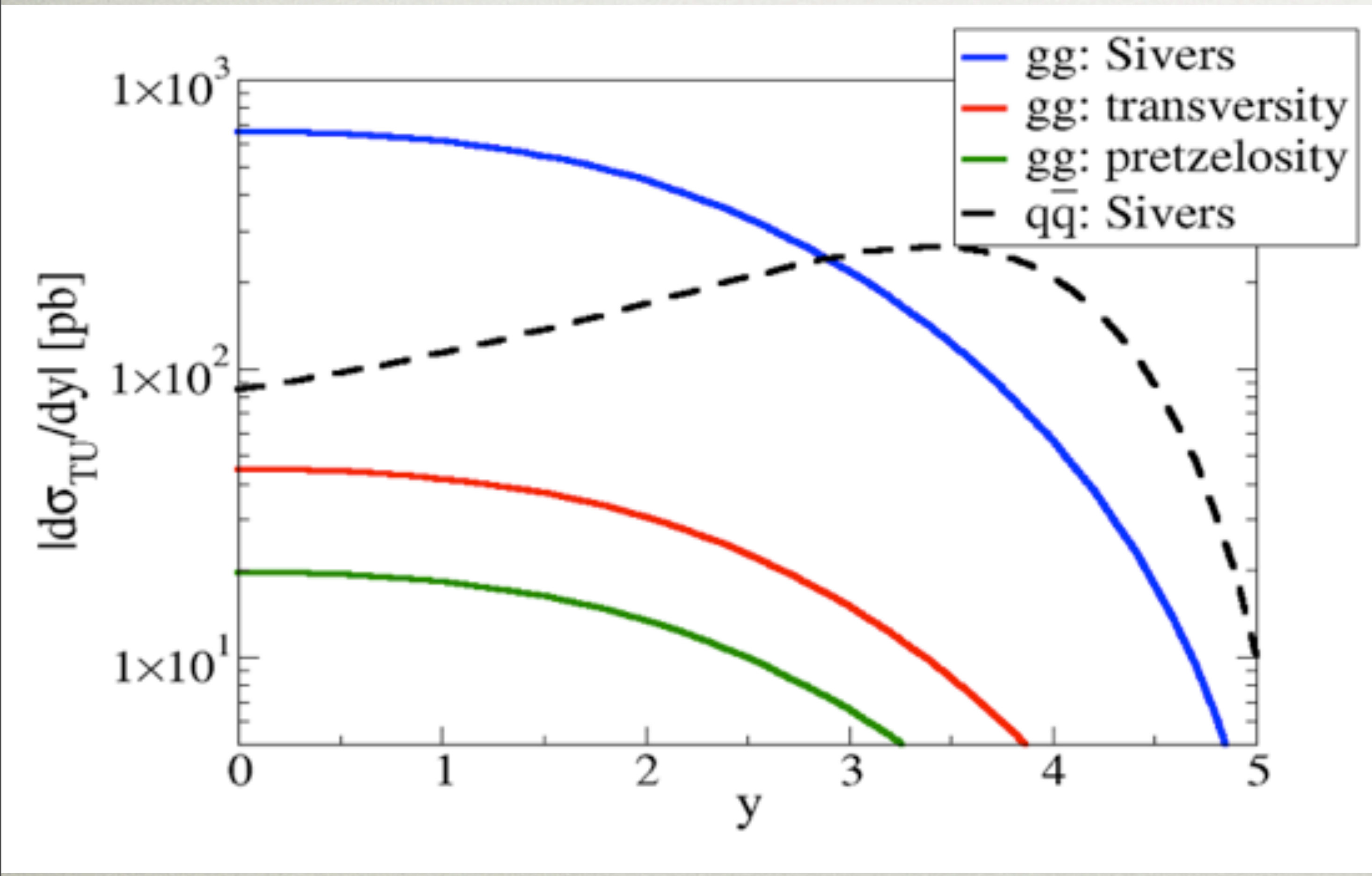

- Gaussian Ansatz + positivity bound for gluon and quark TMDs
- Flavor cancellation for quark Sivers func.

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

  → bound only for u-quarks

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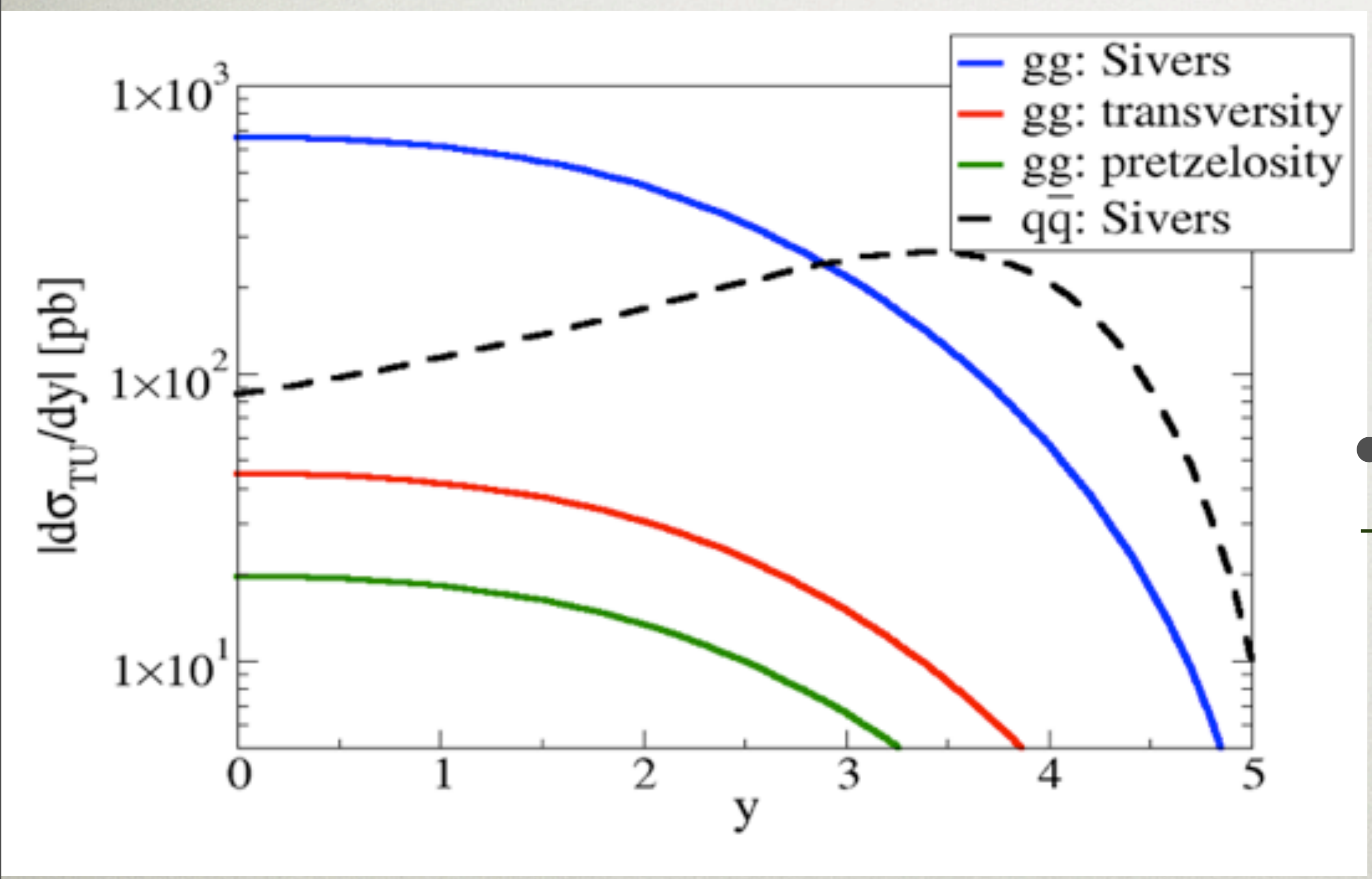

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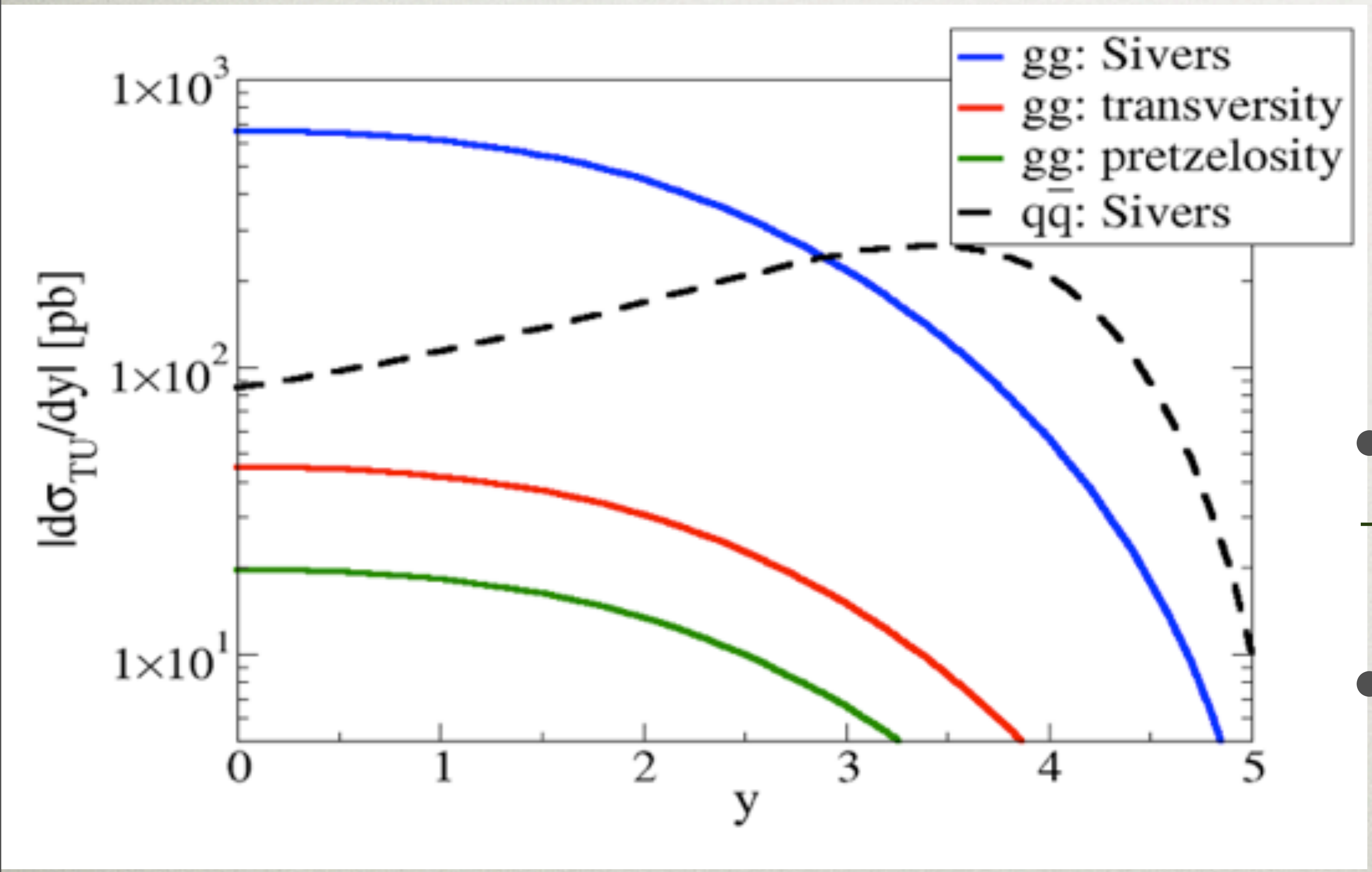

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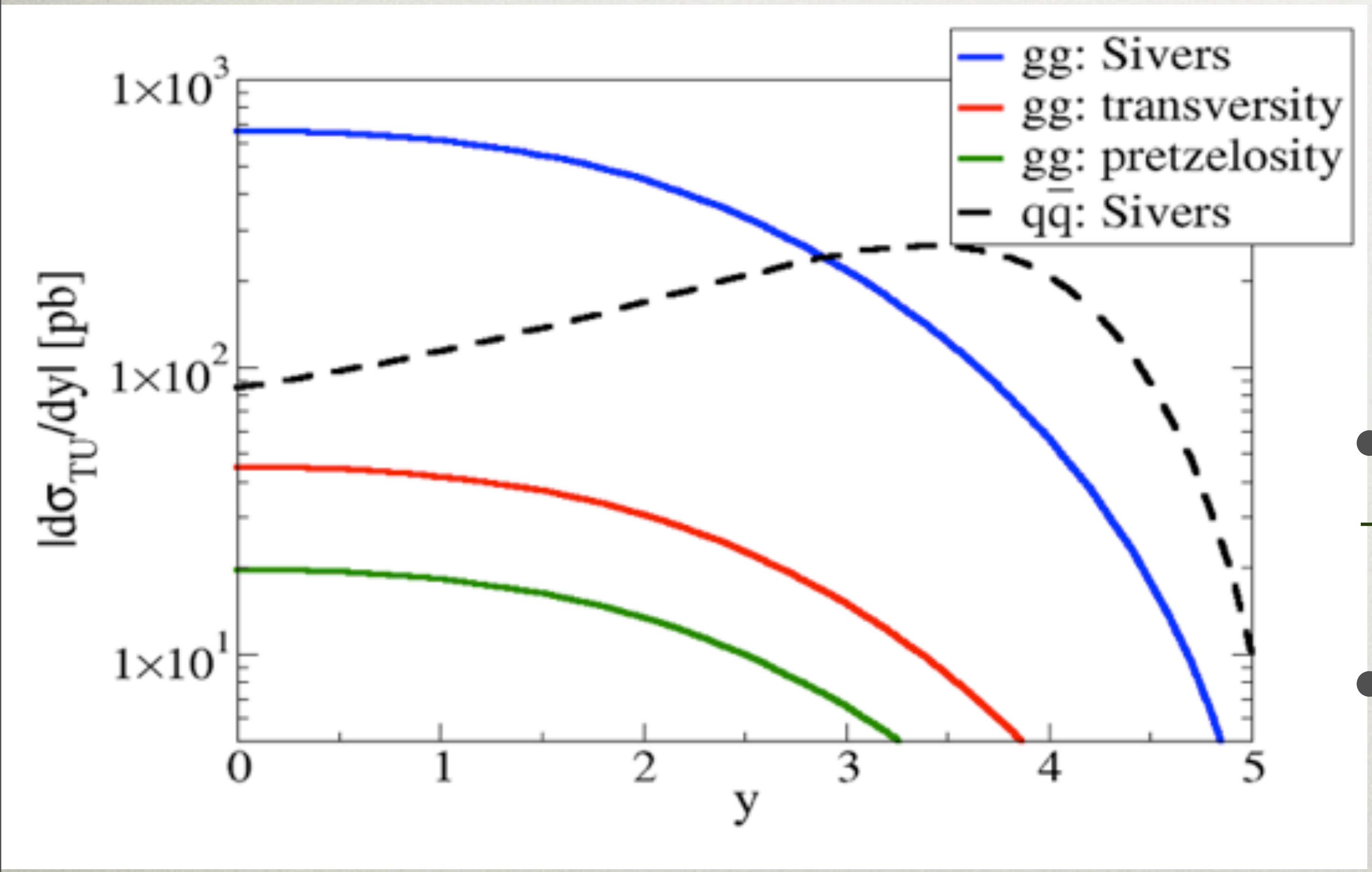

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- Sign not fixed by bound → quark and gluon Sivers effect could add.
- Gluons dominate at mid-rapidity, quarks at large rapidity
- Effects by gluon "transv. / pretzel." small

Diphotons in collinear Factorization

[Nadolsky, Balazs, Berger, Yuan; Catani, Grazzini, de Florian]

Procedure for CSS-resummation:

Diphotons in collinear Factorization

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Procedure for CSS-resummation:

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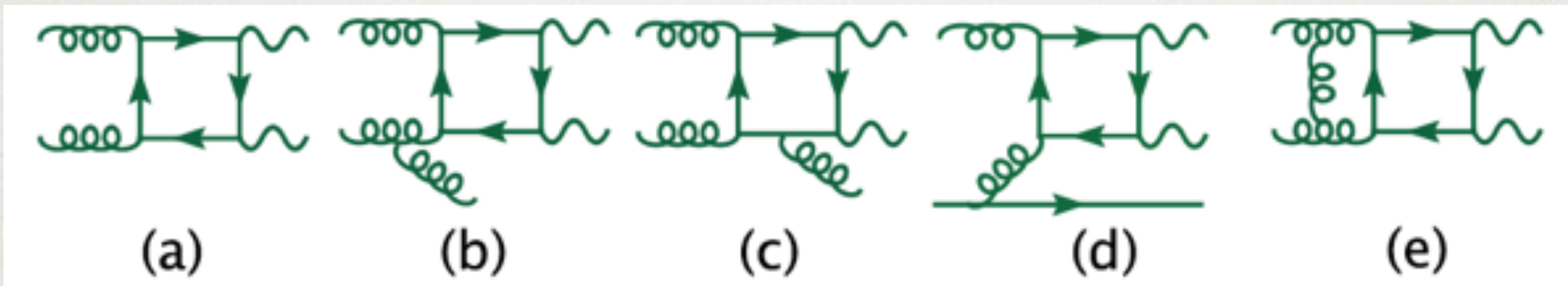

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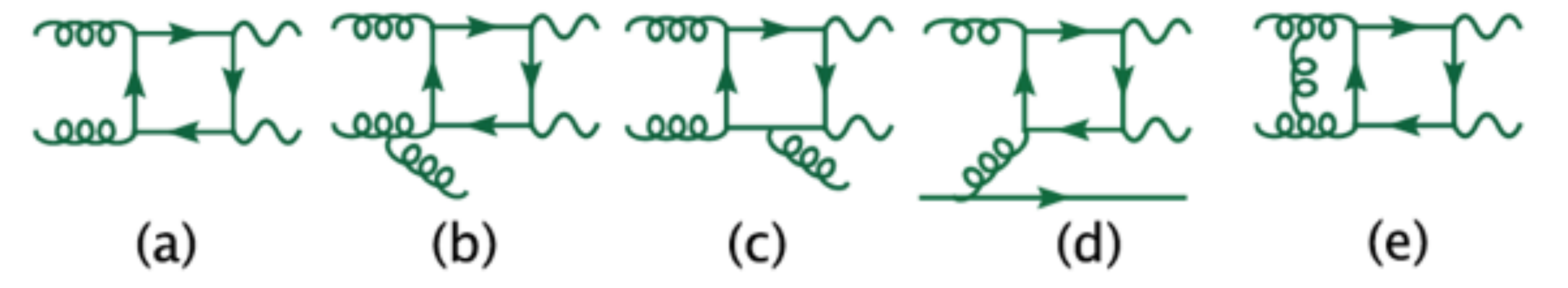

2) $1/q_T$ - expansion for $q_T << Q$

$$\frac{d\sigma}{dy\, dQ^2\, d^2q_T\, d\Omega} = \delta^{(2)}(\vec{q}_T)\, C_\delta(y, Q^2, \Omega) + \left[\frac{\ln(Q^2/q_T^2)}{q_T^2}\right]_+ C_1(y, Q^2, \Omega) + \left[\frac{1}{q_T^2}\right]_+ C_2(y, Q^2, \Omega) + \ldots = W + Y$$

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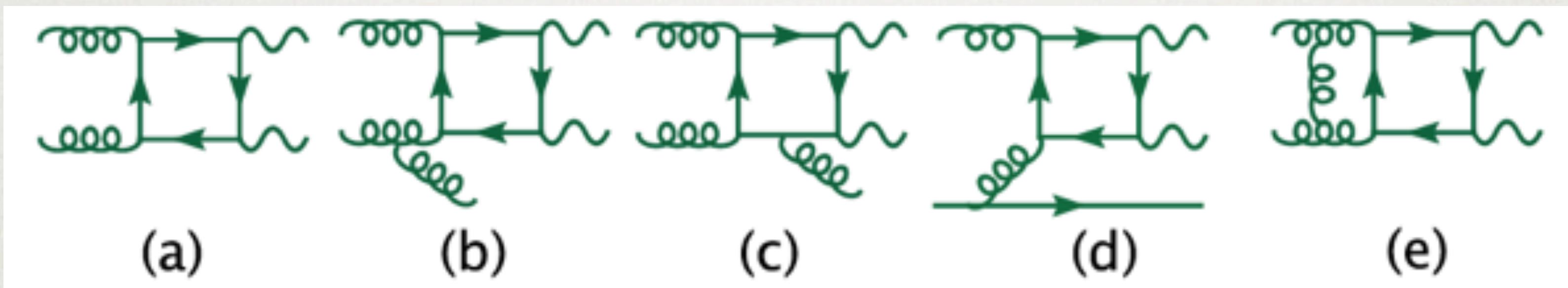

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3) Fourier transform into b_T-space

$$W(Q,Q_T,y,\Omega_*) = \int \frac{d\vec{b}}{(2\pi)^2} e^{i\vec{Q}_T\cdot\vec{b}}\,\tilde{W}(Q,b,y,\Omega_*).$$

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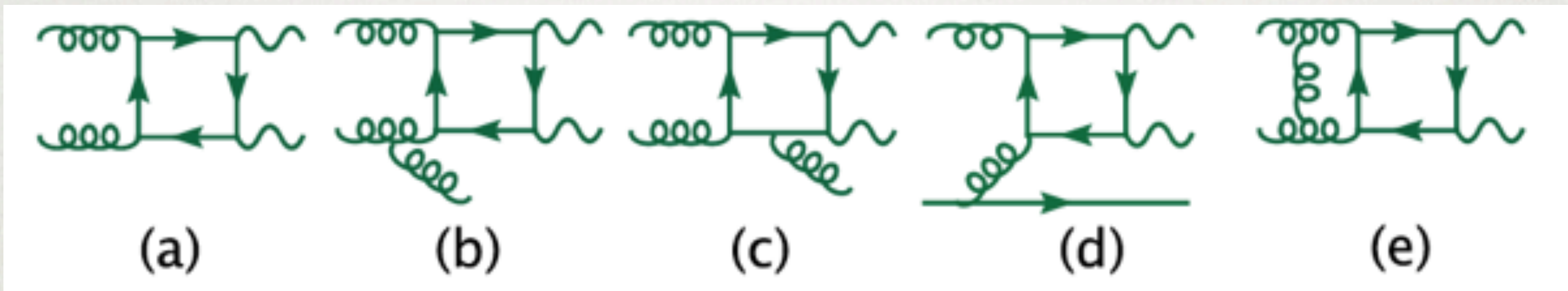

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4) Exponentiate singular logs - resummation

$$S_{\rm Sud}(Q, b_T) = \int_{1/b_T^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left[A\,\ln(Q^2/\mu^2) + B\right]$$

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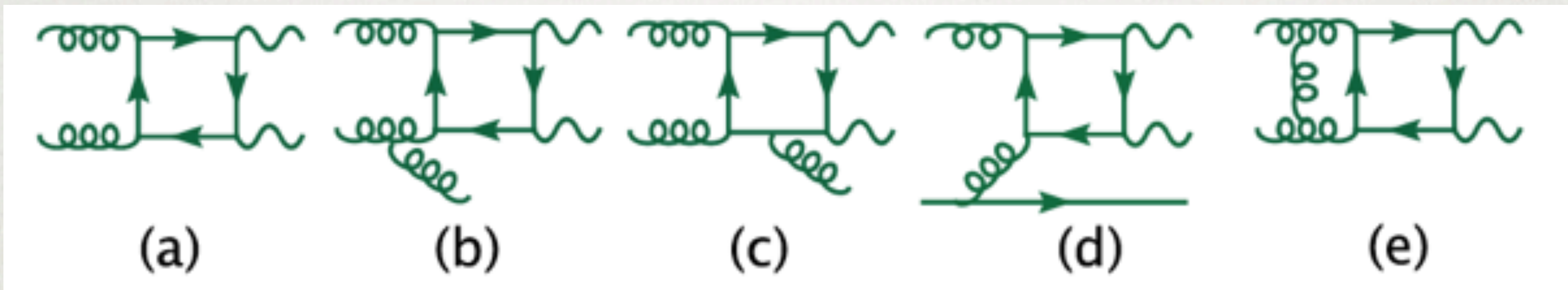

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5) Result

$$\tilde{W}(y, Q, b_T, \Omega) = \mathrm{e}^{S_{\mathrm{Sud}}(Q, b_T)}\Big(F_1(\Omega)(C_q \otimes q)^2 + F_3(\Omega)((C_q \otimes q)(\tilde{C}_q \otimes q) + (\tilde{C}_q \otimes q)(C_q \otimes q)) + (F_2(\Omega) + F_4(\Omega))(\tilde{C}_q \otimes q)^2\Big)(x_a, x_b, 1/b_T)$$

➞ Structure similar to TMD result! ➞ Matching of coll. and TMD formalism

Gluon TMDs in Heavy Ions

[Metz, Zhou; Dominguez, Qiu, Xiao, Yuan]

Definitions for large nuclei A:

Weizsäcker-Williams distribution:

$$M_{\rm WW}^{ij} = \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_\perp\cdot\vec{\xi}_\perp} \langle A|F^{+i}(\xi^- + y^-, \xi_\perp + y_\perp) L^\dagger_{\xi+y} L_y F^{+j}(y^-, y_\perp)|A\rangle$$
$$= \frac{\delta_\perp^{ij}}{2} x f_{1,\rm WW}^g(x, k_\perp) + \left(\frac{1}{2}\hat{k}_\perp^i \hat{k}_\perp^j - \frac{1}{4}\delta_\perp^{ij}\right) x h_{1,\rm WW}^{\perp g}(x, k_\perp),$$

Dipole distribution:

$$M_{\rm DP}^{ij} = 2\int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_\perp\cdot\vec{\xi}_\perp} \langle A|{\rm Tr} F^{+i}(\xi^- + y^-, \xi_\perp + y_\perp) U^{[-]\dagger}_{\xi+y} F^{+j}(y^-, y_\perp) U^{[+]}_{\xi+y}|A\rangle$$
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Color Glass Condensate ➙ classical YM-equations, random color sources

$$F^{+i}(y_\perp) = \partial^+ A^i(y_\perp) = -U(y_\perp)\partial^i_\perp \alpha U^\dagger(y_\perp) \qquad -\nabla^2_\perp \alpha_a(y_\perp) = \rho_a(y_\perp)$$

Matrix elements ➙ Gaussian weighting over color sources $\exp\{-\frac{1}{2}\int d^3x \frac{\rho_a(x)\rho_a(x)}{\lambda_A(x^-)}\}$

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Results:

$$x f^g_{1,\rm WW}(x, k_\perp) \simeq S_\perp \frac{N_c^2 - 1}{4\pi^3} \frac{1}{\alpha_s N_c} \ln\frac{Q_s^2}{k_\perp^2} \qquad (\Lambda_{\rm QCD} \ll k_\perp \ll Q_s)$$

$$x h^{\perp g}_{1,\rm WW}(x, k_\perp) \simeq 2 S_\perp \frac{N_c^2 - 1}{4\pi^3} \frac{\mu_A}{Q_s^2} \qquad (\Lambda_{\rm QCD} \ll k_\perp \ll Q_s)$$

→ no saturation of pos. bound

$$x f^g_{1,\rm WW}(x, k_\perp) \simeq S_\perp \frac{N_c^2 - 1}{4\pi^3} \frac{\mu_A}{k_\perp^2} \qquad (k_\perp \gg Q_s).$$

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→ saturation at large k_T

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$$M^{ij}_{DP} = 2\int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - i\vec{k}_\perp\cdot\vec{\xi}_\perp} \langle A|\mathrm{Tr} F^{+i}(\xi^- + y^-, \xi_\perp + y_\perp) U^{[-]\dagger}_{\xi+y} F^{+j}(y^-, y_\perp) U^{[+]}_{\xi+y}|A\rangle$$
$$= \frac{\delta^{ij}_\perp}{2} x f^g_{1,DP}(x,k_\perp) + \left(\frac{1}{2}\hat{k}^i_\perp \hat{k}^j_\perp - \frac{1}{4}\delta^{ij}_\perp\right) x h^{\perp g}_{1,DP}(x,k_\perp),$$

Color Glass Condensate ➙ classical YM-equations, random color sources

$$F^{+i}(y_\perp) = \partial^+ A^i(y_\perp) = -U(y_\perp)\partial^i_\perp \alpha U^\dagger(y_\perp) \qquad -\nabla^2_\perp \alpha_a(y_\perp) = \rho_a(y_\perp)$$

Matrix elements ➙ Gaussian weighting over color sources $\exp\{-\frac{1}{2}\int d^3x \frac{\rho_a(x)\rho_a(x)}{\lambda_A(x^-)}\}$

Results:

$$x f^g_{1,WW}(x,k_\perp) \simeq S_\perp \frac{N_c^2-1}{4\pi^3}\frac{1}{\alpha_s N_c}\ln\frac{Q_s^2}{k_\perp^2} \qquad (\Lambda_{QCD} \ll k_\perp \ll Q_s)$$
$$x h^{\perp g}_{1,WW}(x,k_\perp) \simeq 2S_\perp \frac{N_c^2-1}{4\pi^3}\frac{\mu_A}{Q_s^2} \qquad (\Lambda_{QCD} \ll k_\perp \ll Q_s)$$

➙ no saturation of pos. bound

$$x f^g_{1,WW}(x,k_\perp) \simeq S_\perp \frac{N_c^2-1}{4\pi^3}\frac{\mu_A}{k_\perp^2} \qquad (k_\perp \gg Q_s)$$
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➙ saturation at large k_T

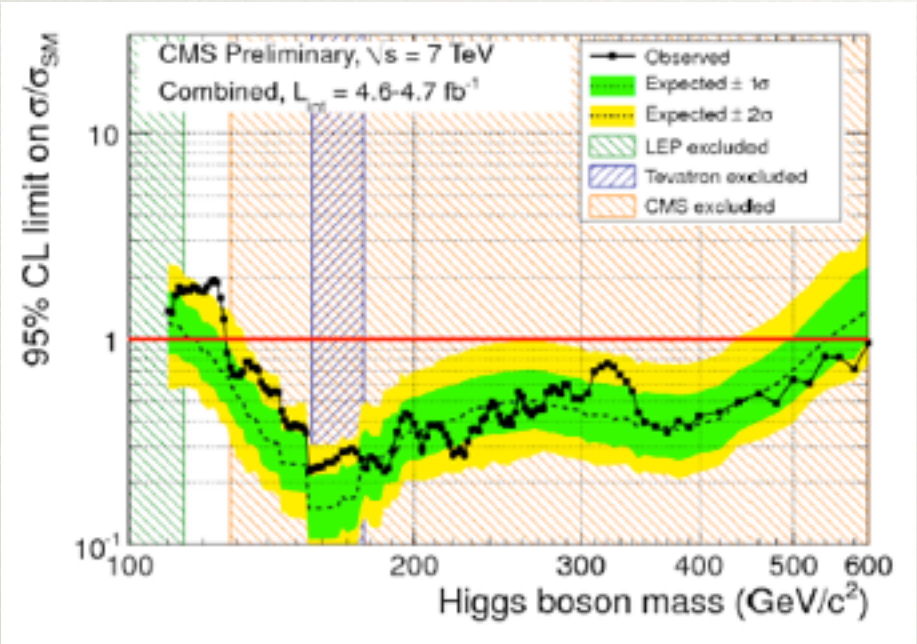
$$x h^{\perp g}_{1,DP}(x,k_\perp) = 2 x f^g_{1,DP}(x,k_\perp) = \frac{k_\perp^2 N_c}{\pi^2 \alpha_s} S_\perp \int \frac{d^2\xi_\perp}{(2\pi)^2} e^{-i k_\perp\cdot\vec{\xi}_\perp} e^{-(Q^2_{sq}\xi^2_\perp/4)}$$

➙ Saturation for all x, k_T!

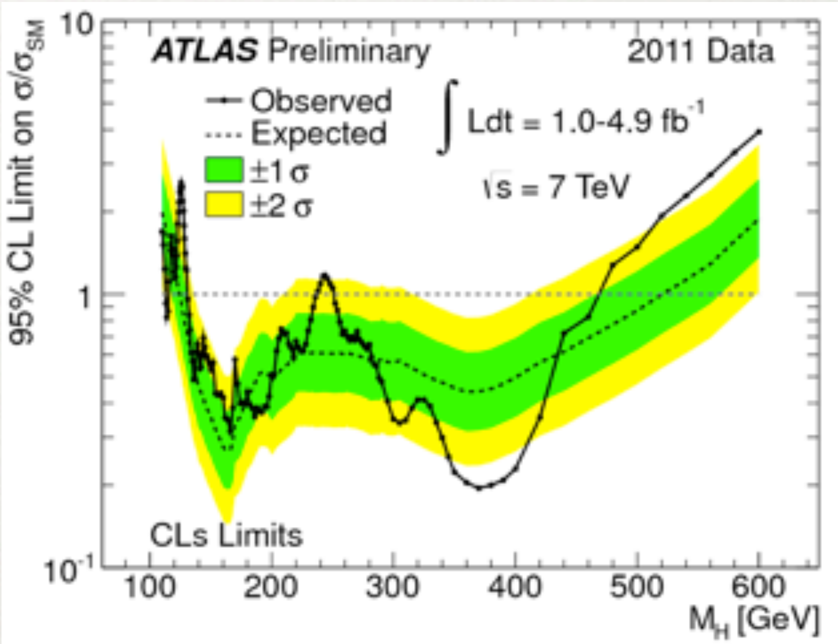
Relation to LHC Physics

<u>Search for the Higgs boson:</u> ➙ mass m_H, total decay width Γ_H

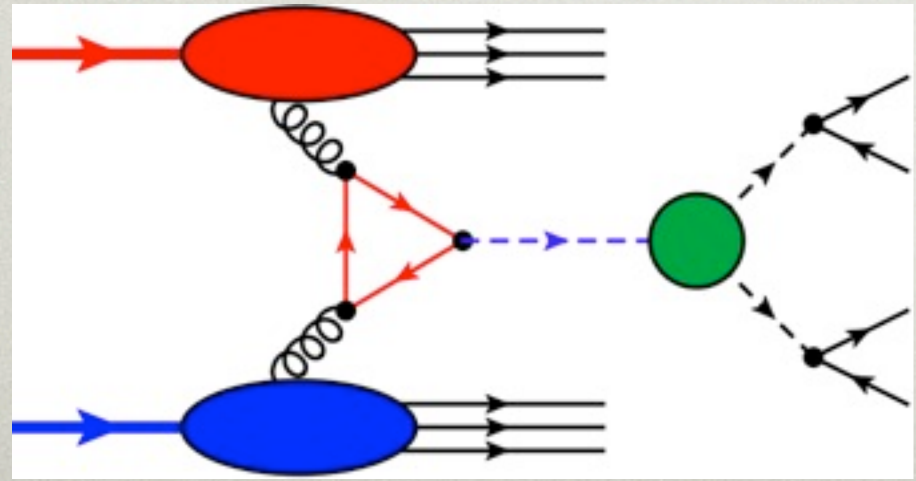
[CMS]



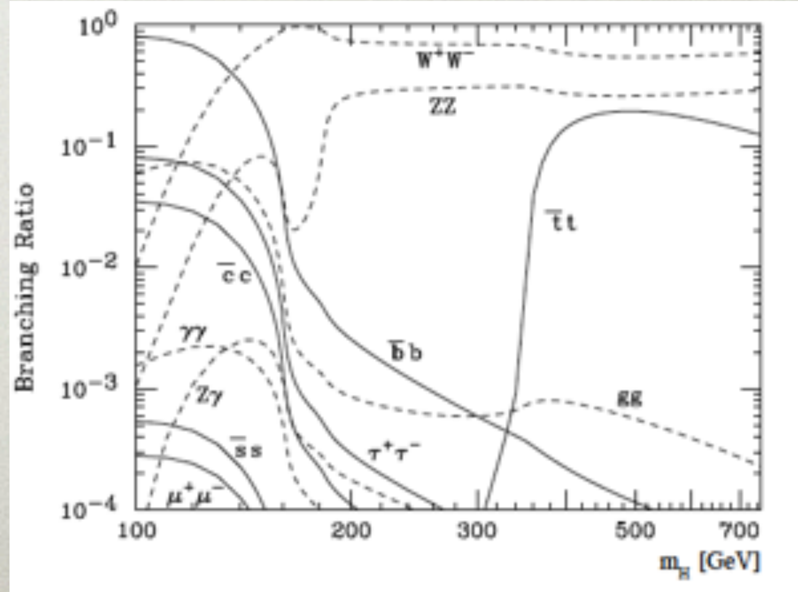
[ATLAS]



main production mechanism: gluon fusion



Higgs decay branching ratio



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

Can gluonic TMDs be useful for the LHC?

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

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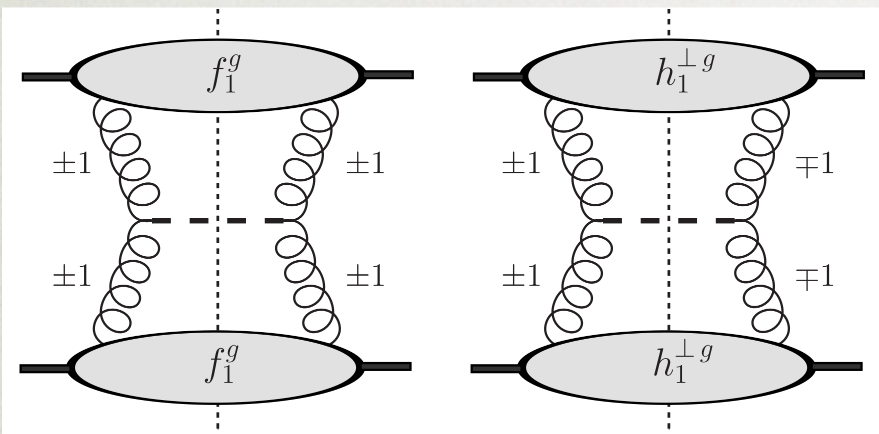

linearly polarized gluons sensitive to Higgs parity

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

+: scalar Higgs   -: pseudoscalar Higgs

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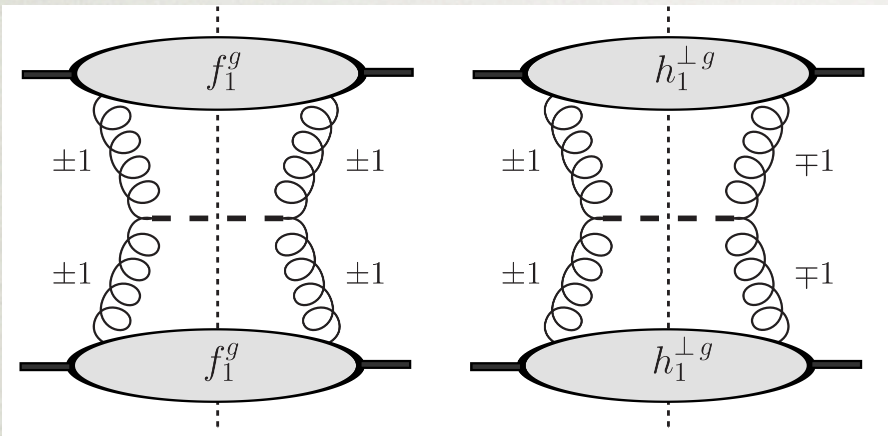

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q_T-behaviour:

$$\boxed{R = \frac{[h_1^{\perp g} \otimes h_1^{\perp g}]}{[f_1^g \otimes f_1^g]}}$$

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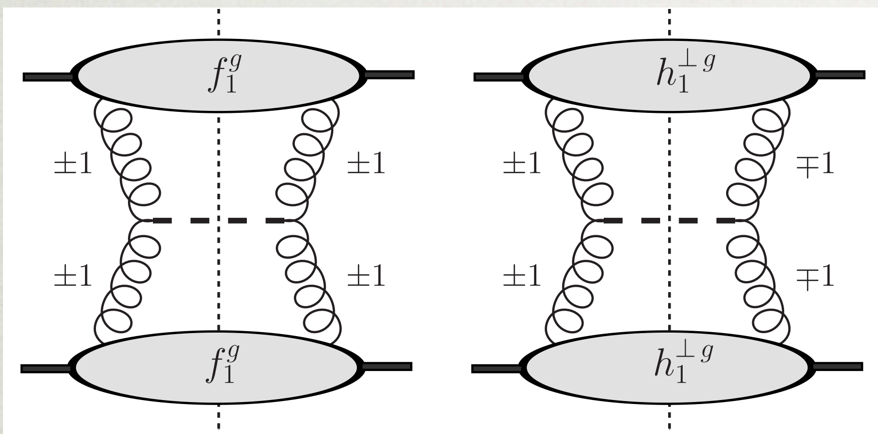

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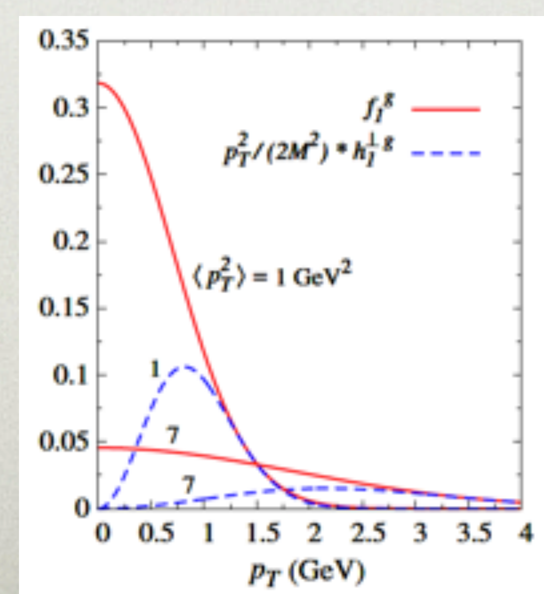
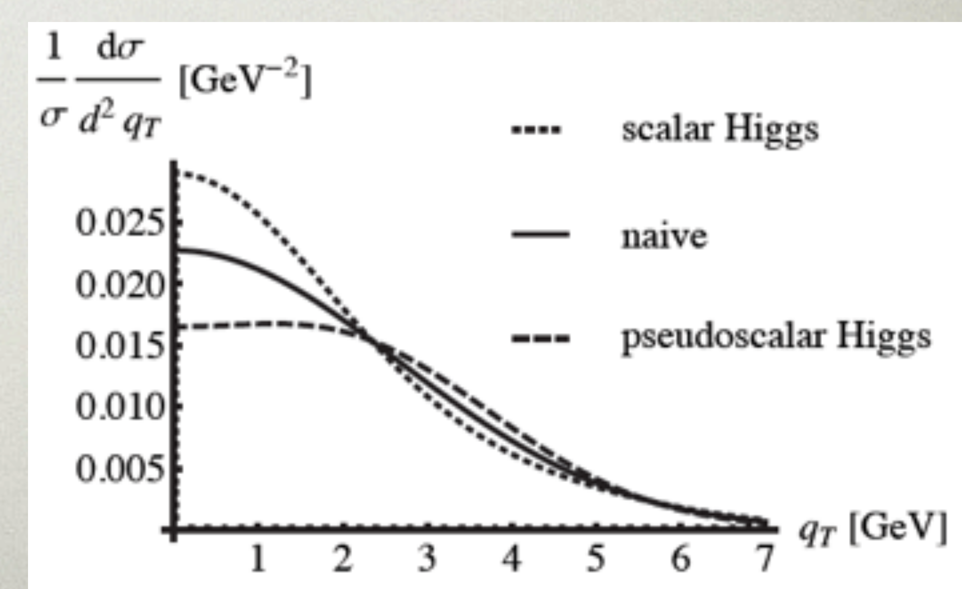
Numerical estimate:

Gaussian ansatz + saturation

$<p_T^2> = 7$ GeV^2

$$\boxed{\frac{1}{\sigma}\frac{d\sigma}{d^2\vec{q}_T} = [1 \pm R(q_T)]\,\frac{1}{2\pi\langle p_T^2\rangle}\,e^{-q_T^2/2\langle p_T^2\rangle}}$$





Resummed gluon TMDs in Higgs Production

[Sun, Xiao, Yuan, PRD 84,094005]

Use of “old-fashioned” TMD approach to derive CSS-resummation for pure Higgs production: $P_a + P_b \to H + X$

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1) Start from "unsubtracted" TMDs + soft factor ➙ common hard part at one-loop order

$$\boxed{\begin{aligned}\frac{d\sigma}{dM^2 d^2 q_T} = H(M^2,\mu^2,\rho) \int d^2k_{aT} d^2k_{bT} d^2l_T\, \delta^{(2)}(\vec{k}_{aT}+\vec{k}_{bT}+\vec{l}_T-\vec{q}_T) \times \\ S(\vec{l}_T,\mu,\rho)\Big(f_{1,a}^{g,\mathrm{unsub}}\, f_{1,b}^{g,\mathrm{unsub}} + w\, h_{1,a}^{\perp g,\mathrm{unsub}}\, h_{1,b}^{\perp g,\mathrm{unsub}}\Big)\end{aligned}}$$

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2) Derive CS - equations:

$$\boxed{\xi \frac{\partial}{\partial \xi} \Gamma_U^{ij,\mathrm{unsub}}(x, b_T, x\xi, \mu, \rho) = (K_g + G_g) \Gamma_U^{ij,\mathrm{unsub}}(x, b_T, x\xi, \mu, \rho)}$$

$$\boxed{K_g + G_g = -\frac{\alpha_s C_A}{\pi} \ln \frac{x^2 \xi^2 b_T^2}{4} \mathrm{e}^{2\gamma_E - 3/2}}$$

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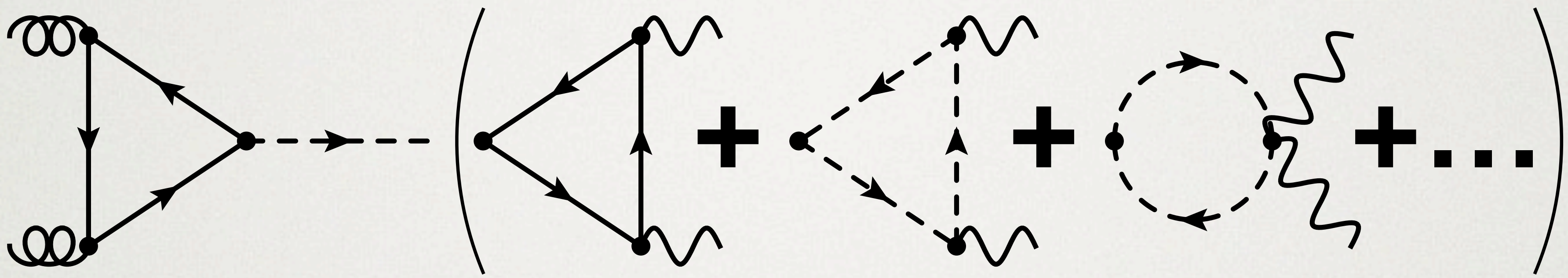
4) Perturbative tail of the gluon TMDs:

$$\boxed{f_1^g\otimes f_1^g + h_1^{\perp g}\otimes h_1^{\perp g} = \int d^2b_T\, \mathrm{e}^{-iq_T\cdot b_T}\Big[\mathrm{e}^{-S_{\text{Sud}}(M^2,1/b_T^2)}\Big((C_q\otimes q)^2 + (\tilde{C}_q\otimes q)^2\Big)\Big)(x_a,x_b,1/b_T)}$$

➙ agrees with conventional collinear resummation approach [Catani, Grazzini]

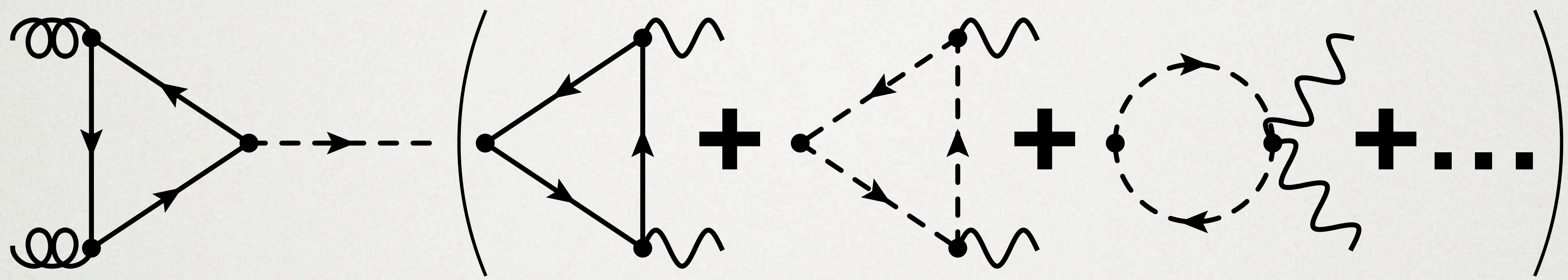
Including Higgs decay: gg → H/A → γγ



<u>ϕ - integrated cross section of Higgs + box:</u>

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

Including Higgs decay: $gg \to H/A \to \gamma\gamma$



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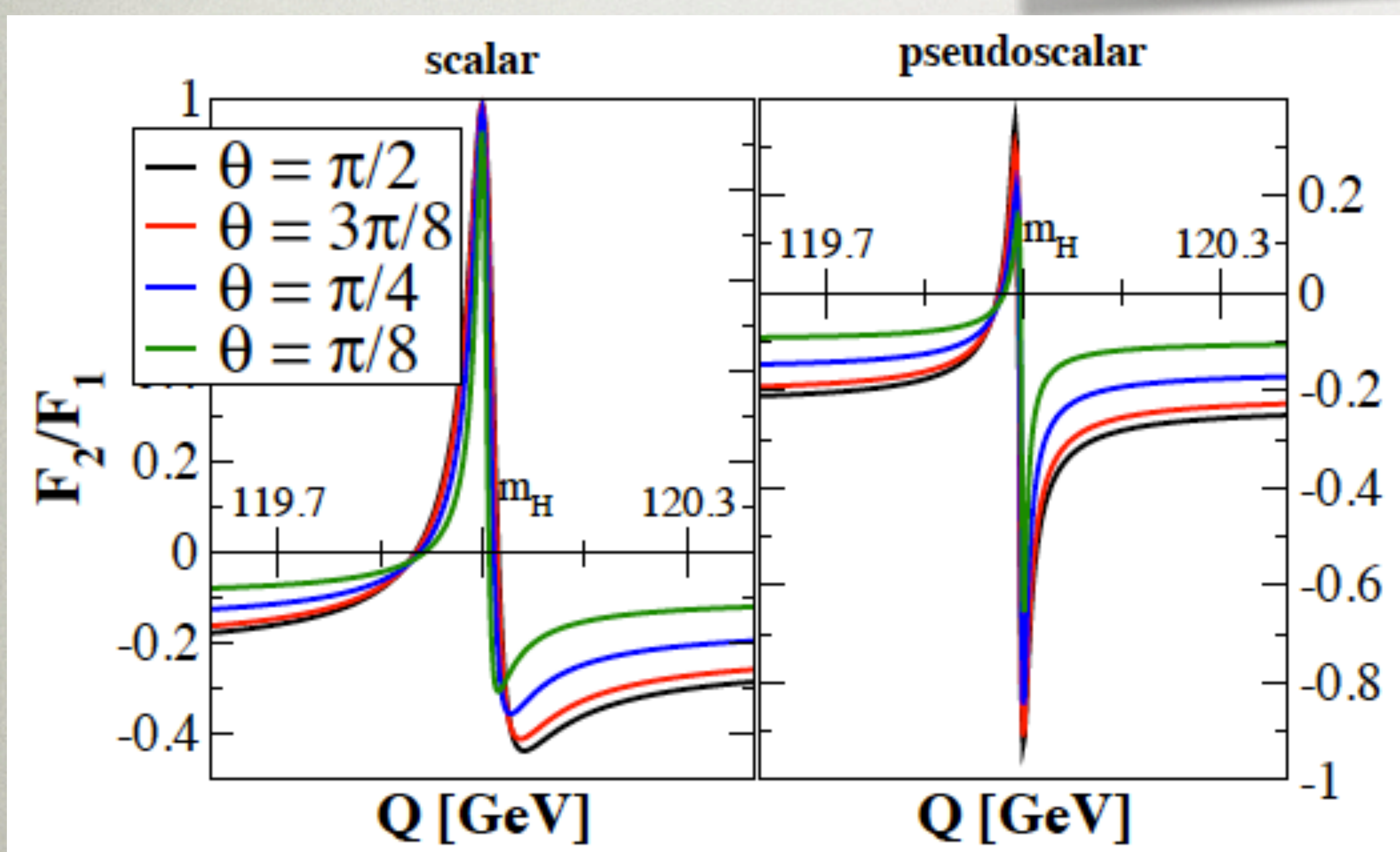


$Q \neq m_H$: $\bar{\mathcal{F}}_1 \gg \bar{\mathcal{F}}_2$

box dominant

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

Higgs dominant (pole of the propagator)

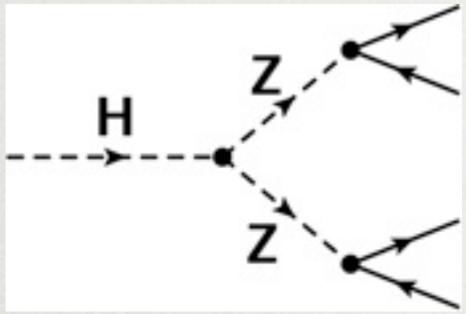
Sign signature preserved at the pole!
small total Higgs width → good Q resolution

4 Lepton Production

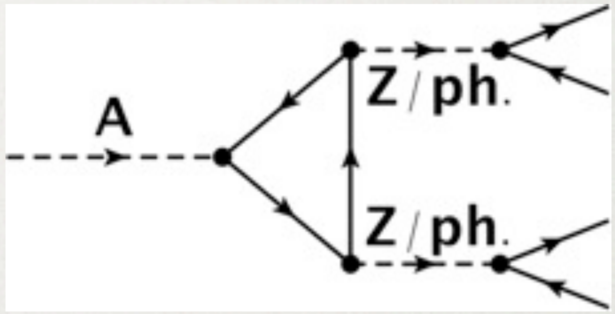
[Boer, den Dunnen, Pisano, MS, Vogelsang, in prep.]

Different decay channels for scalar and pseudoscalar Higgs:

SM Higgs: tree-level vertex



BSM pseudoscalar Higgs: top-loop



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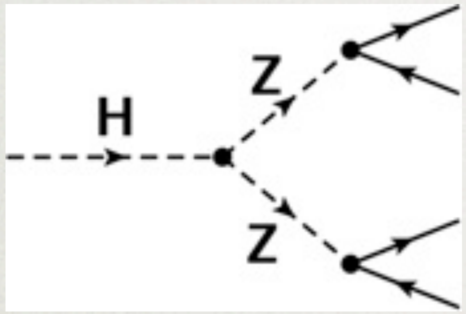

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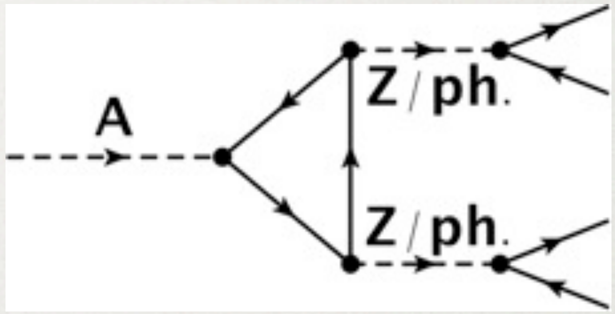
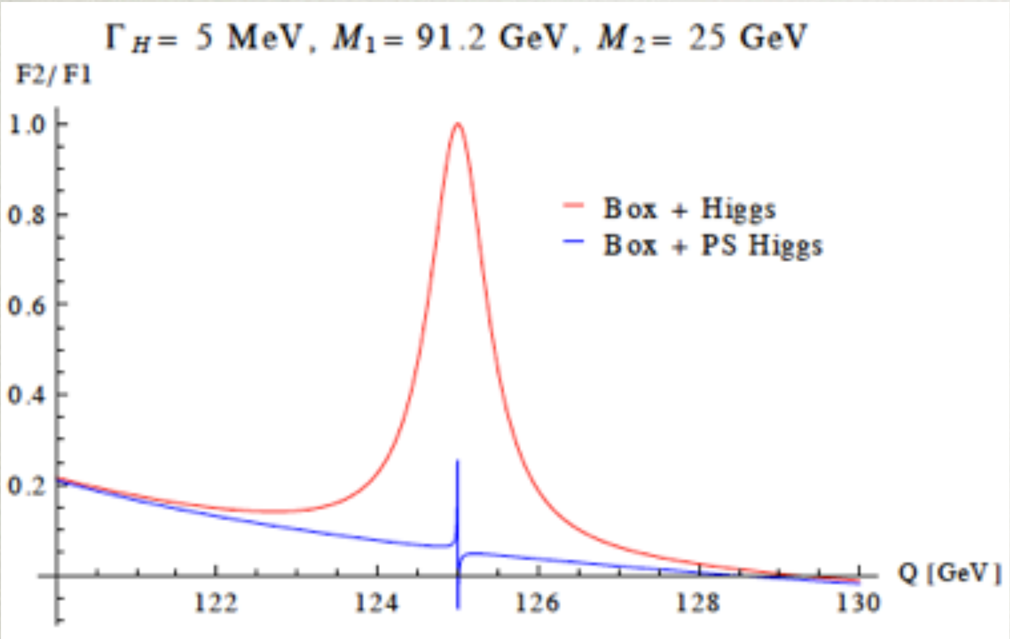


one on-shell Z: gg → ZZ*



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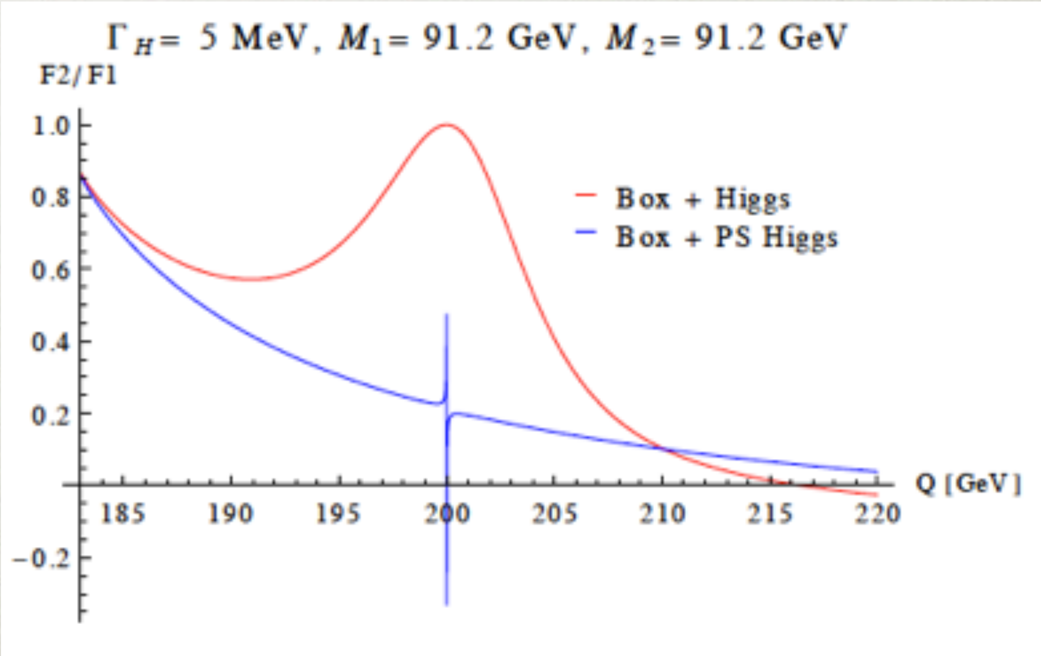


➙ more difficult w.r.t. parity distinction, clean process experimentally

Warning: multi-parton scattering!

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

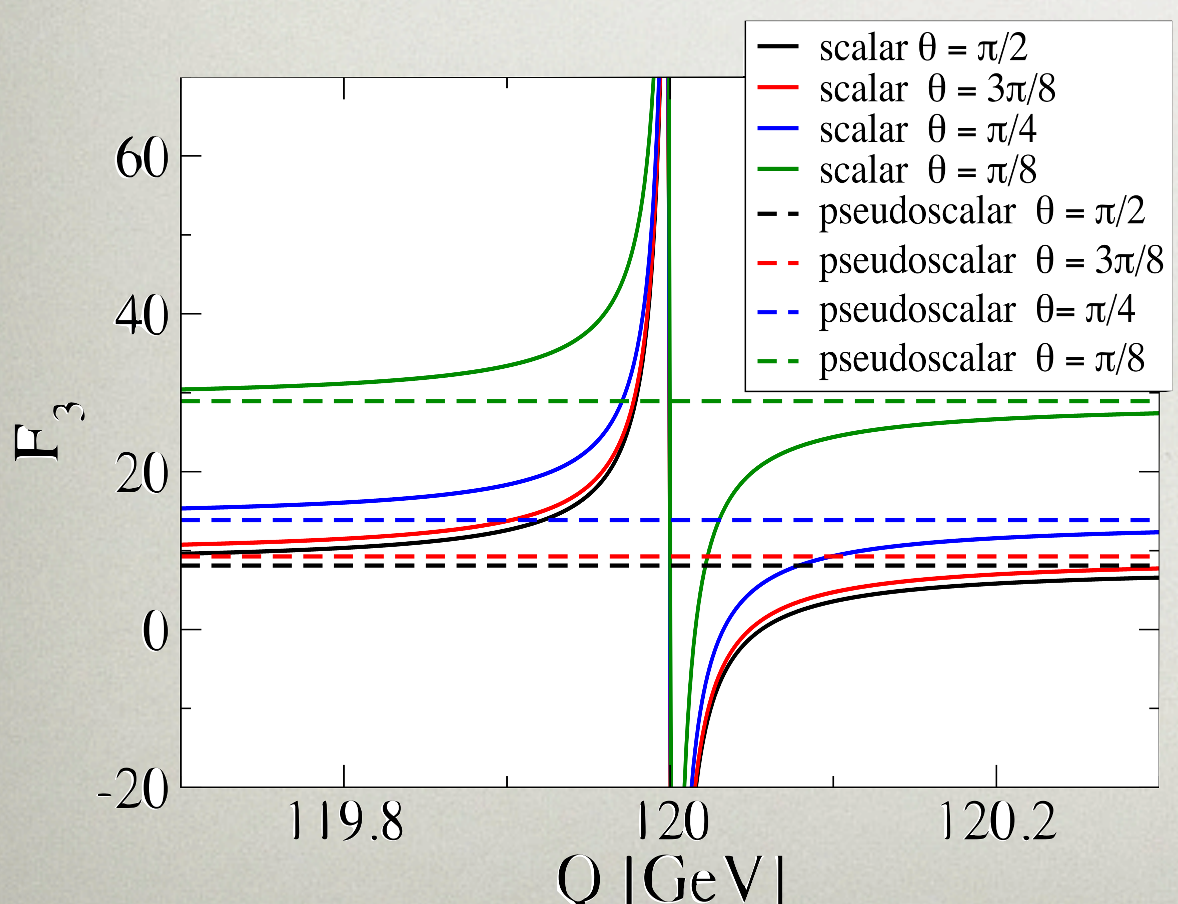
[Boer, den Dunnen, Pisano, MS, Vogelsang, in prep.]

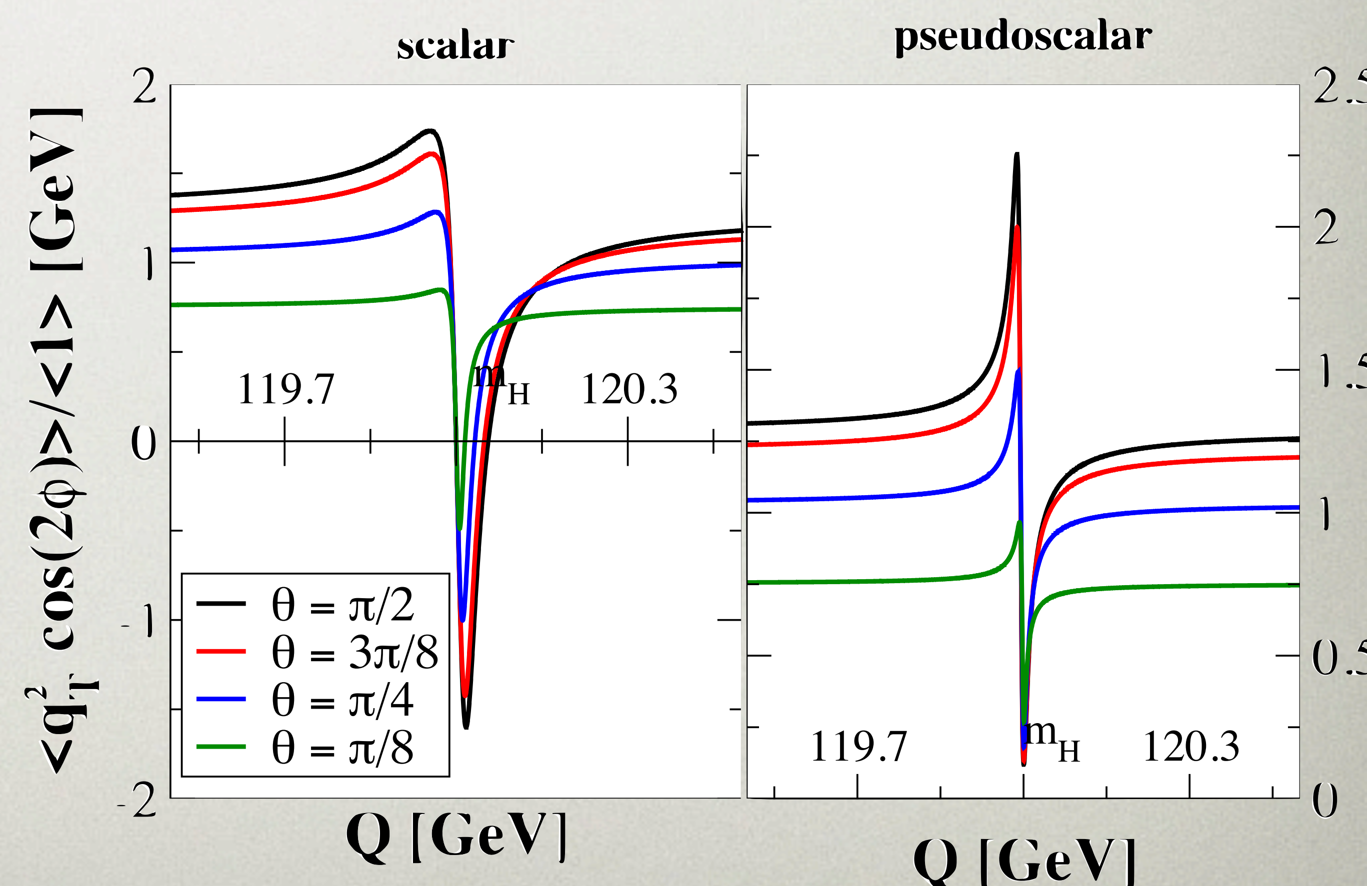
$$\langle q_T^2\, \cos(2\phi)\rangle = \int d^2q_T\, d\phi\, q_T^2 \cos(2\phi)\, \frac{d\sigma}{d^4q\, d\Omega} \sim \bar{\mathcal{F}}_3(\theta, Q^2) \left[f_1^g \otimes h_1^{\perp g} + h_1^{\perp g} \otimes f_1^g \right]$$

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

→ offers alternative determination of Higgs parity

→ theoretically cleaner (yes/no decision), experimentally harder

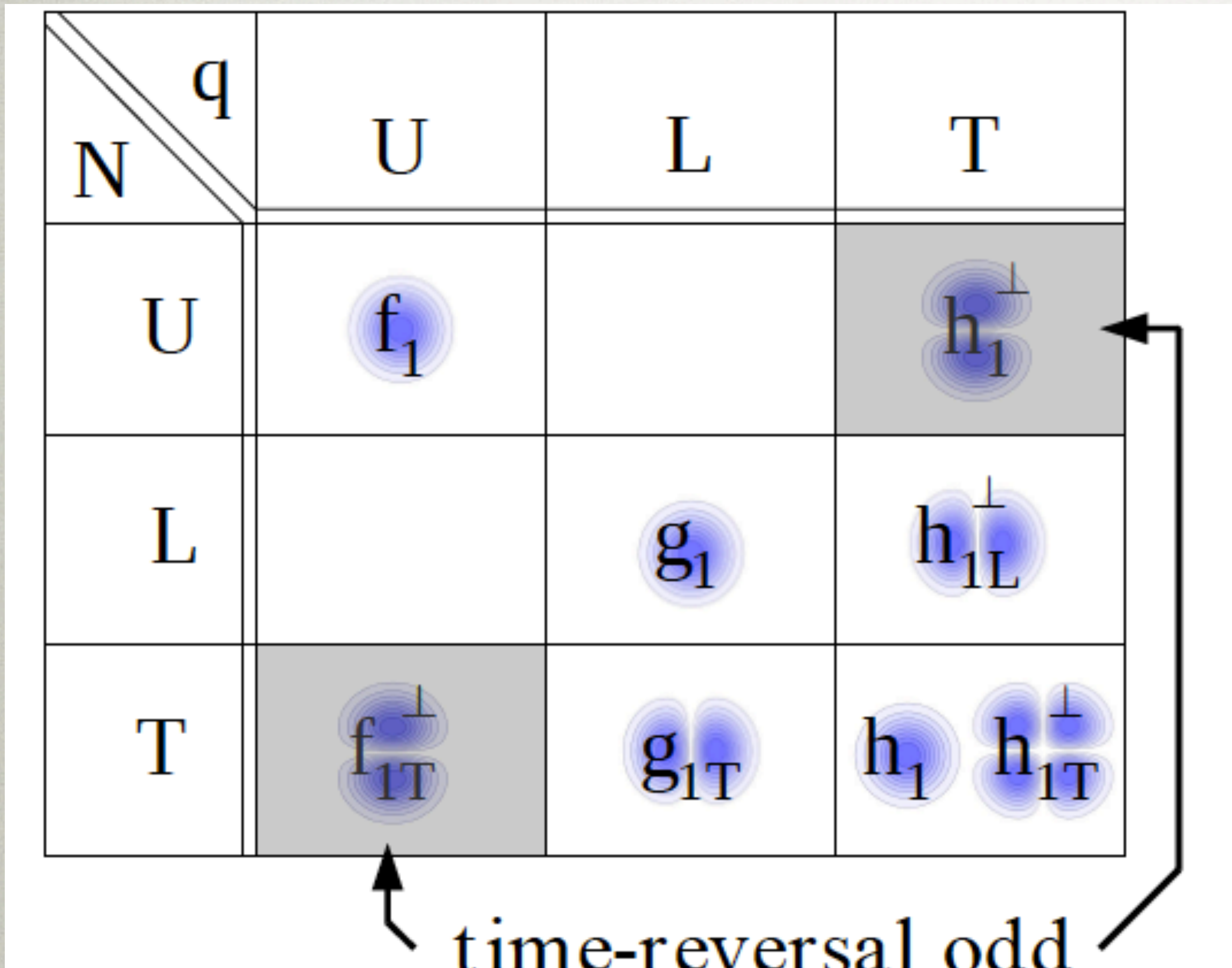




Summary

- Several alternative processes to DY at the LHC
- Gluon TMDs accessible at the LHC and RHIC
- Distribution of linearly polarized gluons from cos(4ϕ) - mode
- Linearly polarized gluons may be useful to pin down the parity of Higgs bosons
- Gluon Sivers- and Boer-Mulders effect may be feasible at RHIC (if $\neq 0$)
- To Do: Evolution of gluon TMDs

Spin-Dependent TMDs



Plot courtesy of B. Musch

well-studied :

[experimentally & theoretically]

Sivers function

Boer-Mulders function

(naive) collinear limits:

unpolarized, helicity, transversity

"wormgear" functions

"pretzelosity"

quadrupole structure