# TMD effects in Higgs and J/

Wilco den Dunnen
Liverpool 30-10-2013

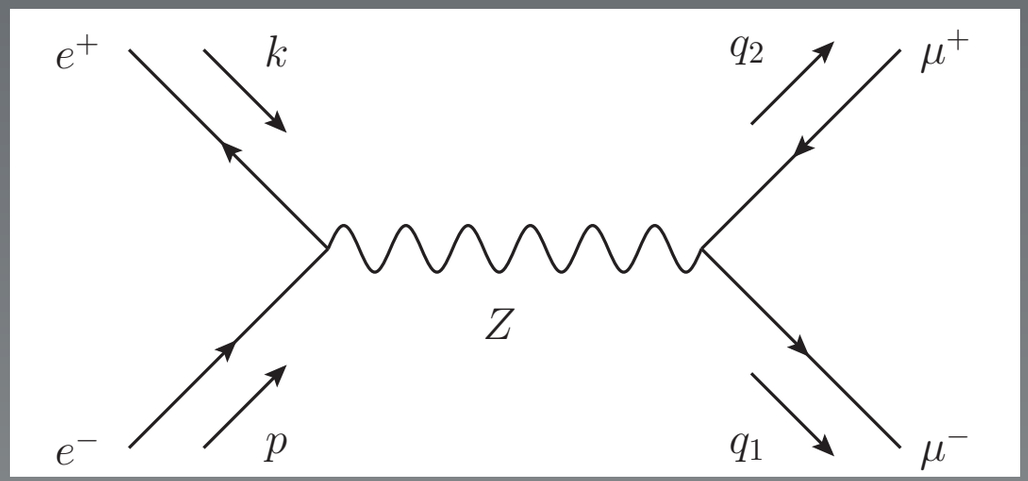
EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

# OUTLINE

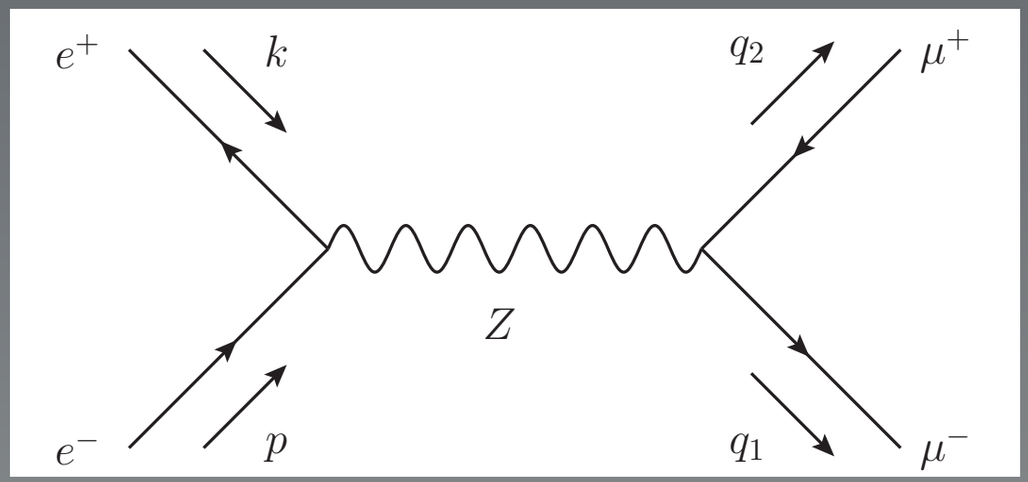
- **Intro TMD factorization**
- Calculation of TMDs
- TMD effects in Higgs production
- How to measure the gluon TMDs

# INTRO TMD FACTORIZATION

# ELECTRON-POSITRON SCATTERING

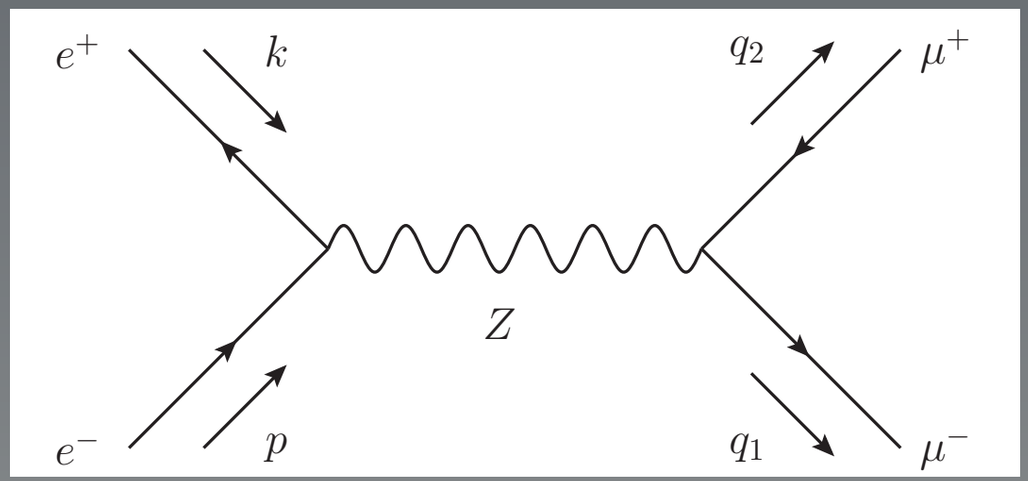


# ELECTRON-POSITRON SCATTERING



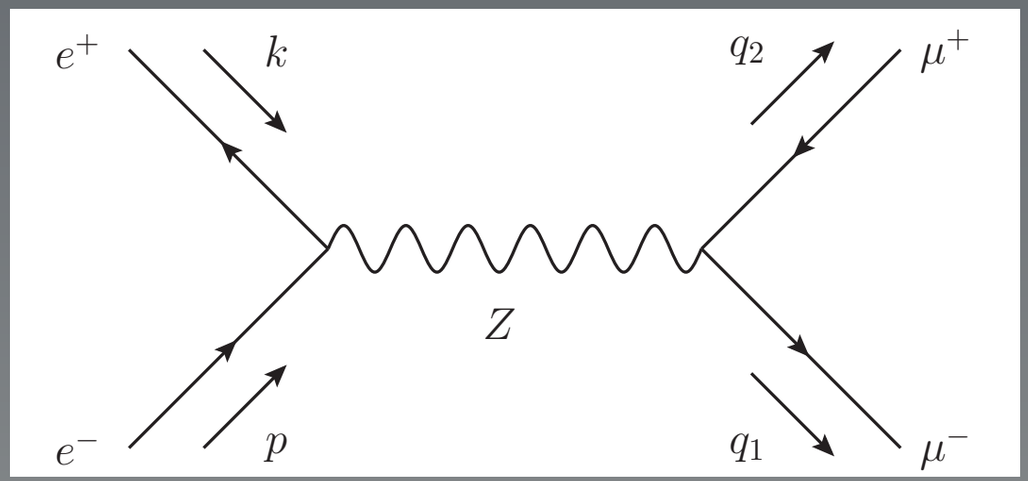

$\overline{v}(k)$

# ELECTRON-POSITRON SCATTERING



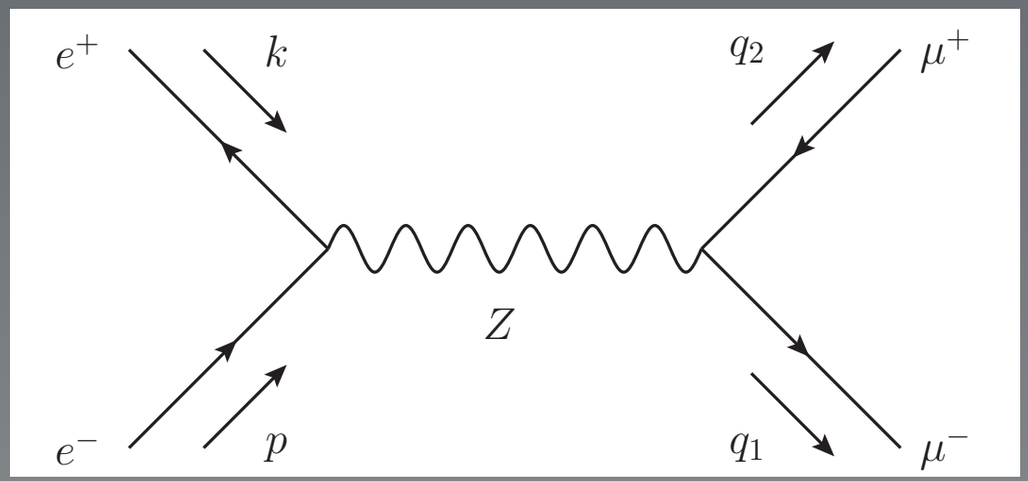

$$\overline{v}(k)\frac{-ig}{4\cos\theta_w}\gamma^\mu\left[(1-4\sin^2\theta_w)-\gamma_5\right]$$

# ELECTRON-POSITRON SCATTERING



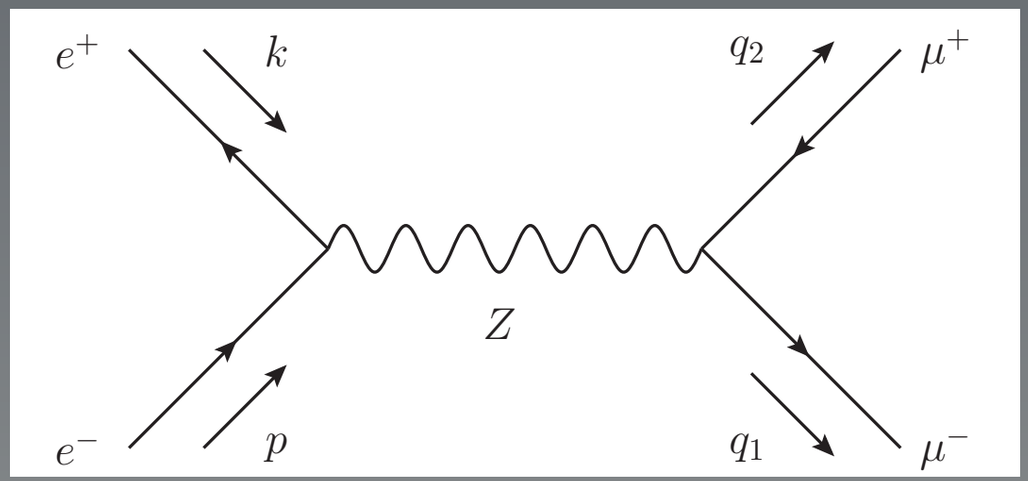

$$\overline{v}(k)\frac{-ig}{4\cos\theta_w}\gamma^\mu\Big[(1-4\sin^2\theta_w)-\gamma_5\Big]u(p)$$

# ELECTRON-POSITRON SCATTERING



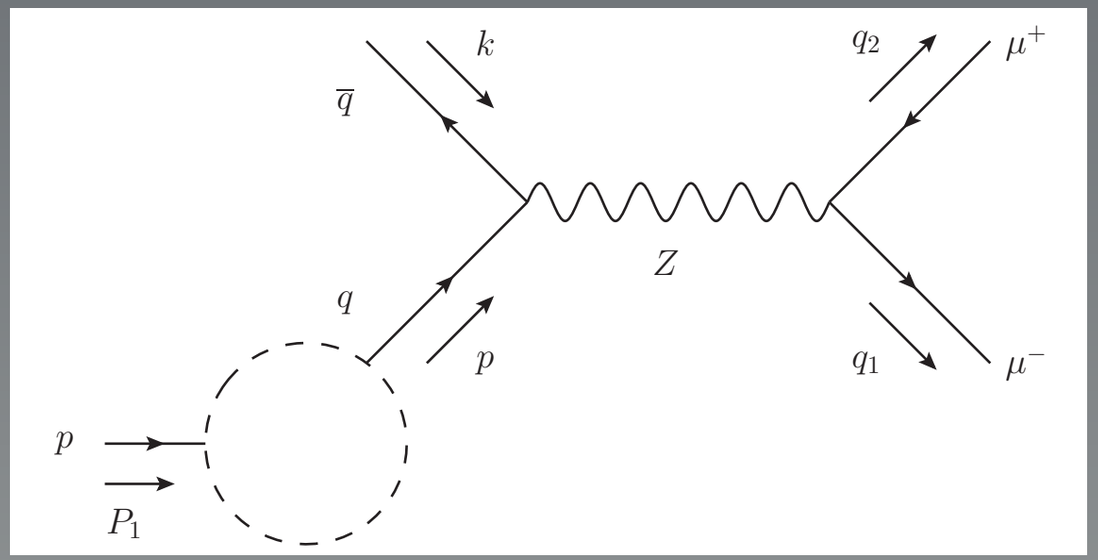

$$\overline{v}(k)\frac{-ig}{4\cos\theta_w}\gamma^\mu\Big[(1-4\sin^2\theta_w)-\gamma_5\Big]u(p)\frac{-ig_{\mu\nu}}{q^2-M_Z^2+i0}$$

# ELECTRON-POSITRON SCATTERING

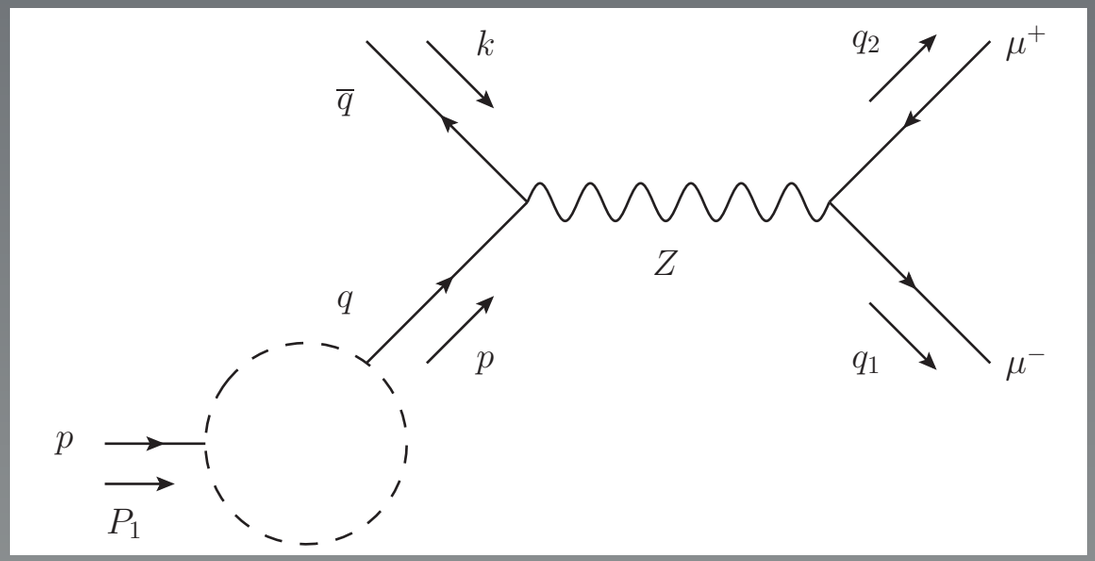



$$\overline{v}(k)\frac{-ig}{4\cos\theta_w}\gamma^\mu\Big[(1-4\sin^2\theta_w)-\gamma_5\Big]u(p)\frac{-ig_{\mu\nu}}{q^2-M_Z^2+i0}\overline{u}(q_1)\frac{-ig}{4\cos\theta_w}\gamma^\nu\Big[(1-4\sin^2\theta_w)-\gamma_5\Big]v(q_2)$$

# PROTON-PROTON SCATTERING

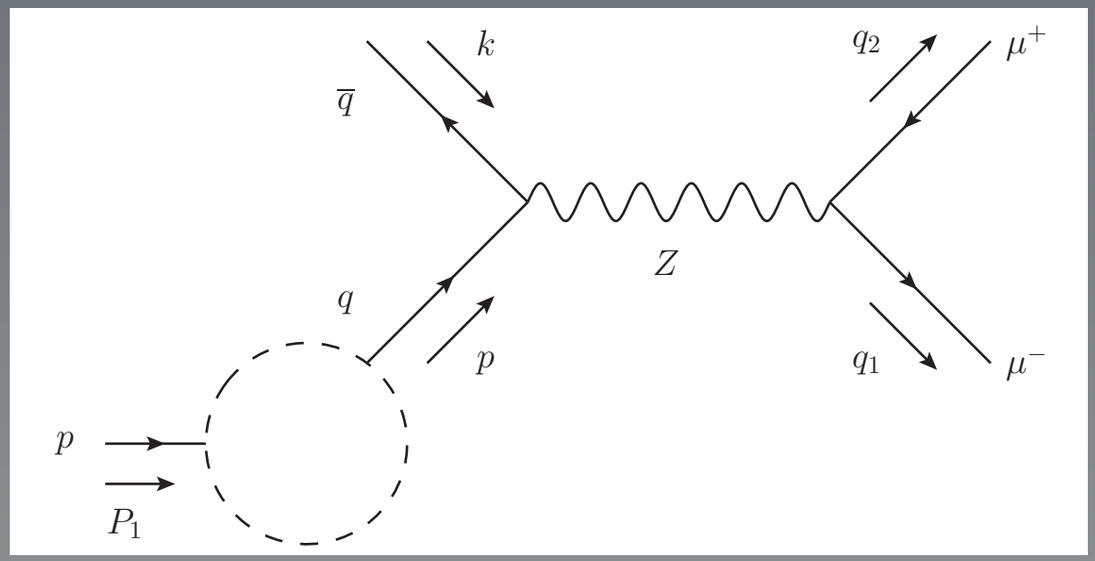


# PROTON-PROTON SCATTERING



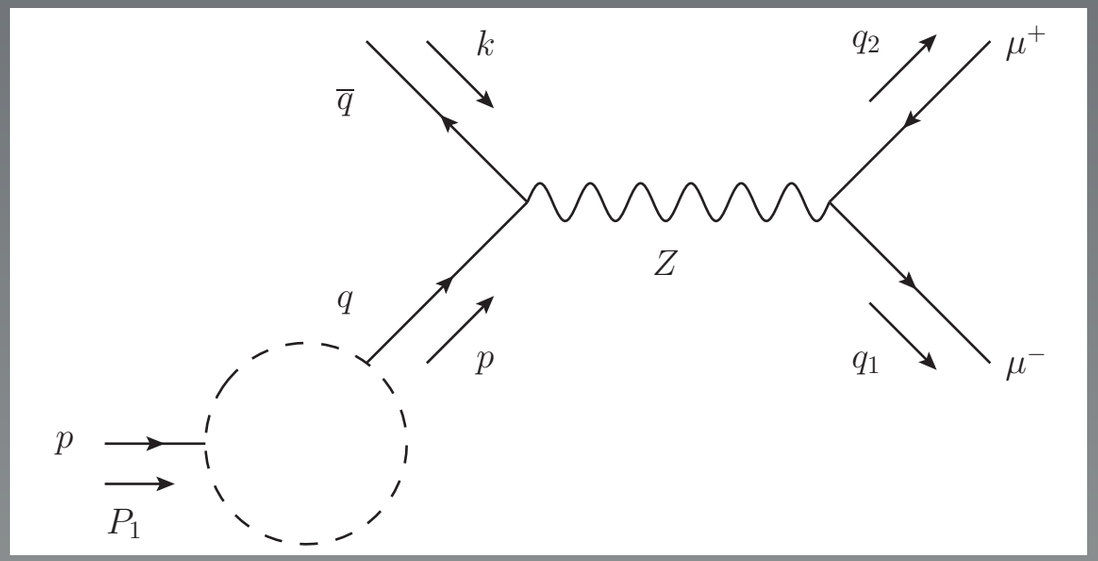

$$\Psi|P_1\rangle$$

# PROTON-PROTON SCATTERING



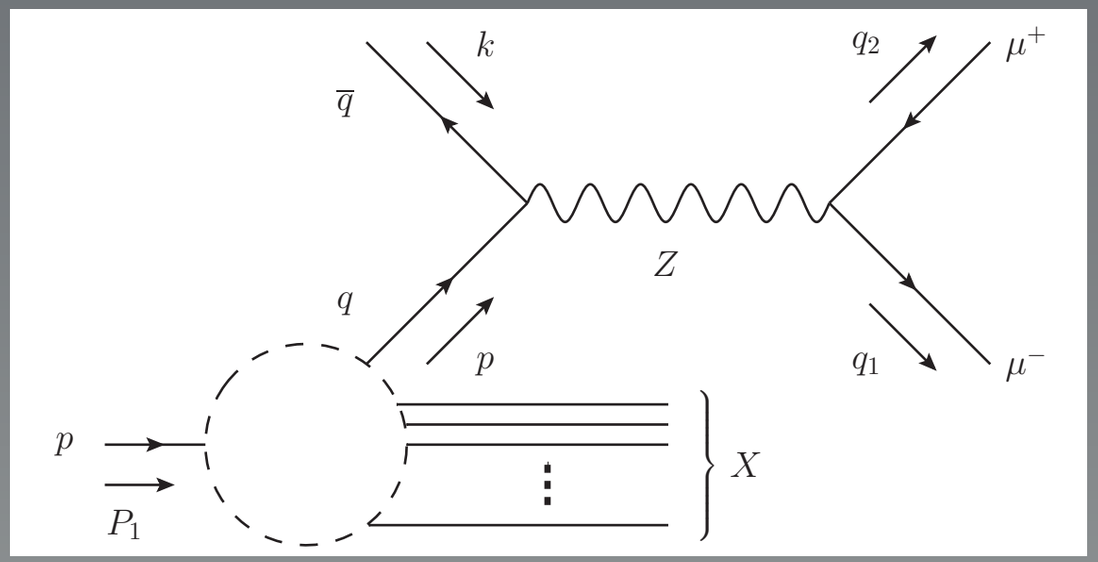

$$\Psi|P_1\rangle \qquad \Rightarrow \qquad u(P_1)$$

# PROTON-PROTON SCATTERING




$$\Psi|P_1\rangle \qquad \Rightarrow \qquad ?$$

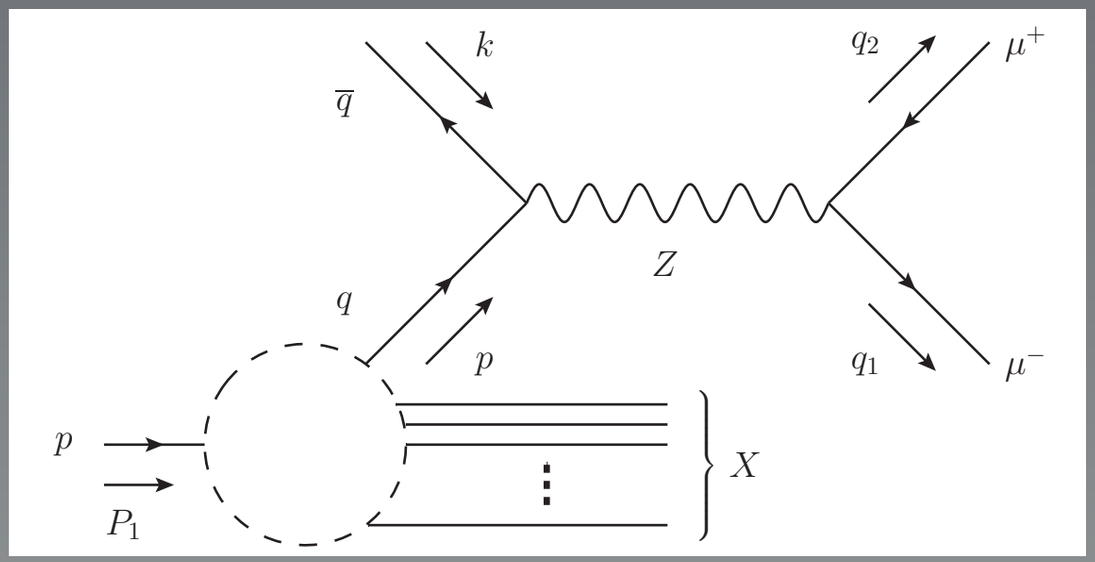
# PROTON-PROTON SCATTERING




$$\Psi|P_1\rangle \quad \Rightarrow \quad \langle X|\Psi|P_1\rangle$$

# PROTON-PROTON SCATTERING

$$\mathcal{M}^{pp\to\mu^+\mu^- X} =$$



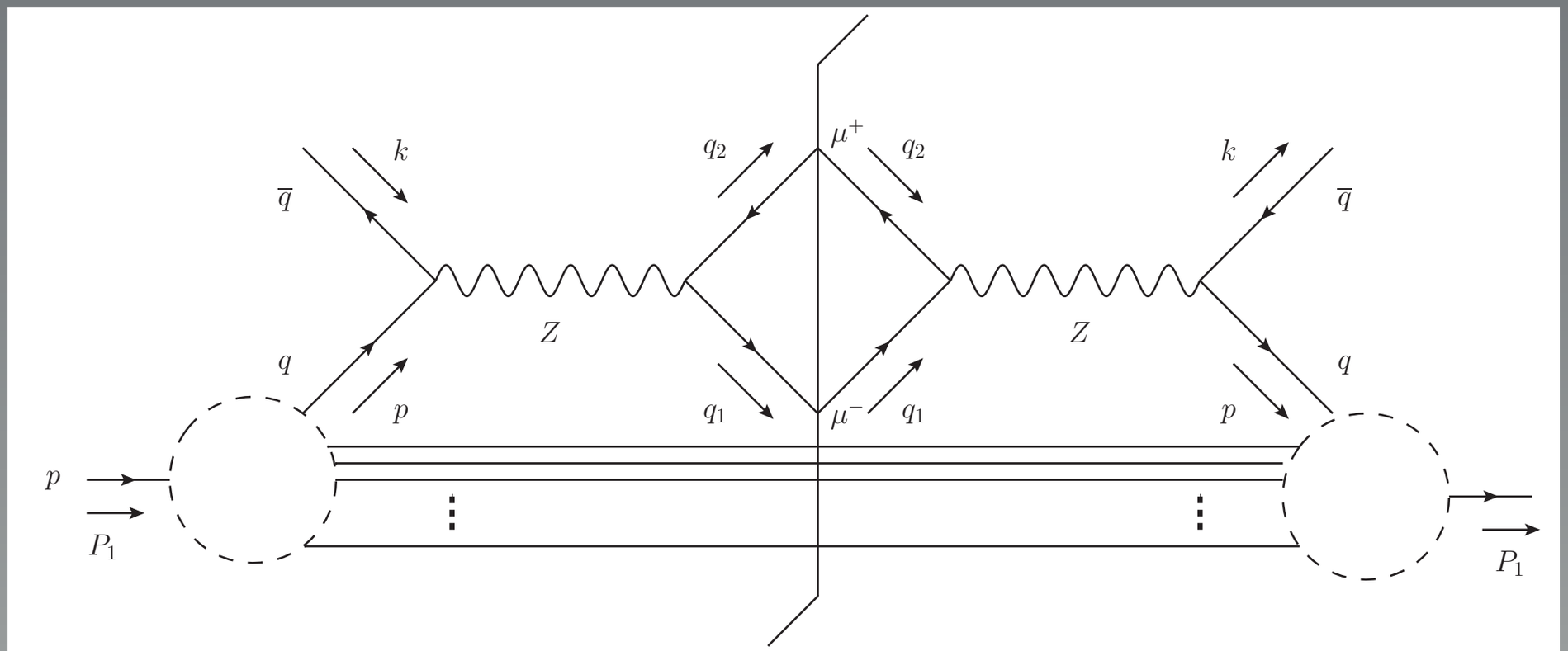

$$\langle X|\Psi|P_1\rangle$$

# PROTON-PROTON SCATTERING

$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X} \left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$

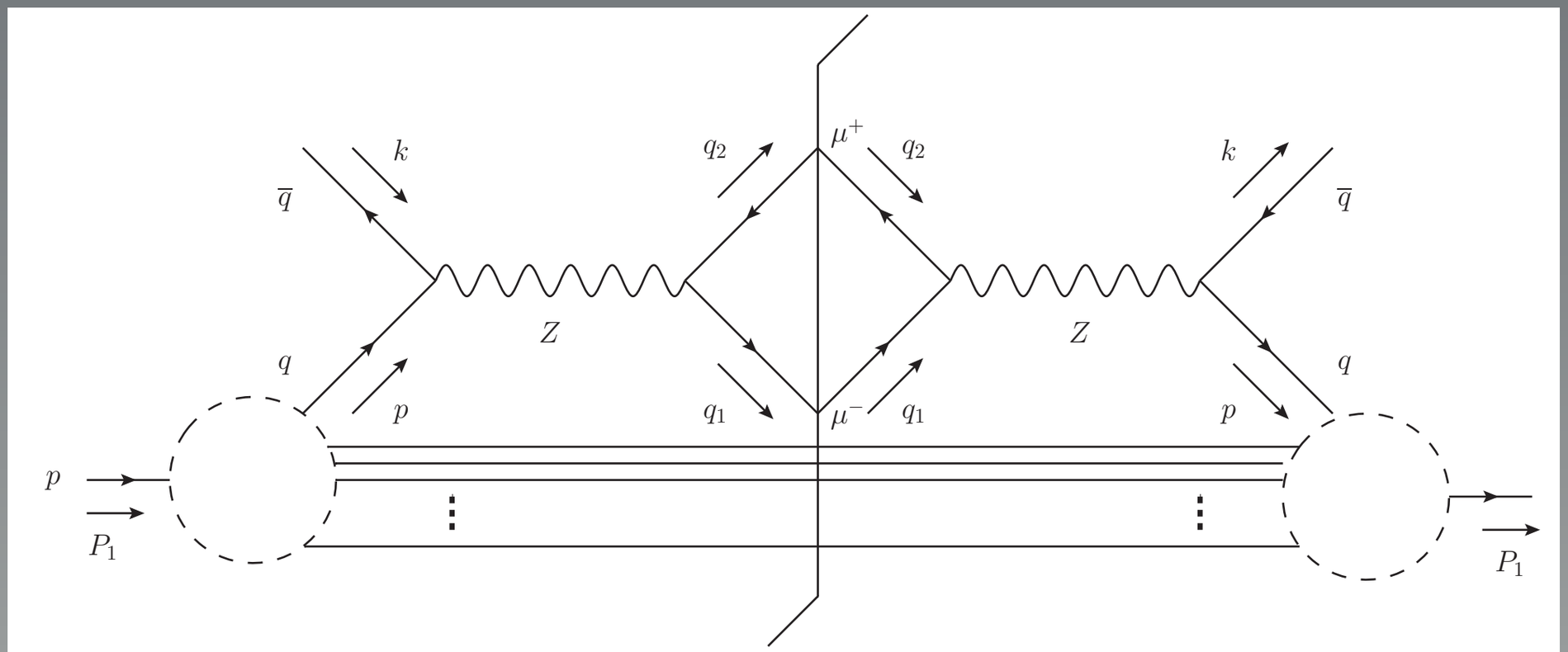
# PROTON-PROTON SCATTERING

$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X}\left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$



# PROTON-PROTON SCATTERING

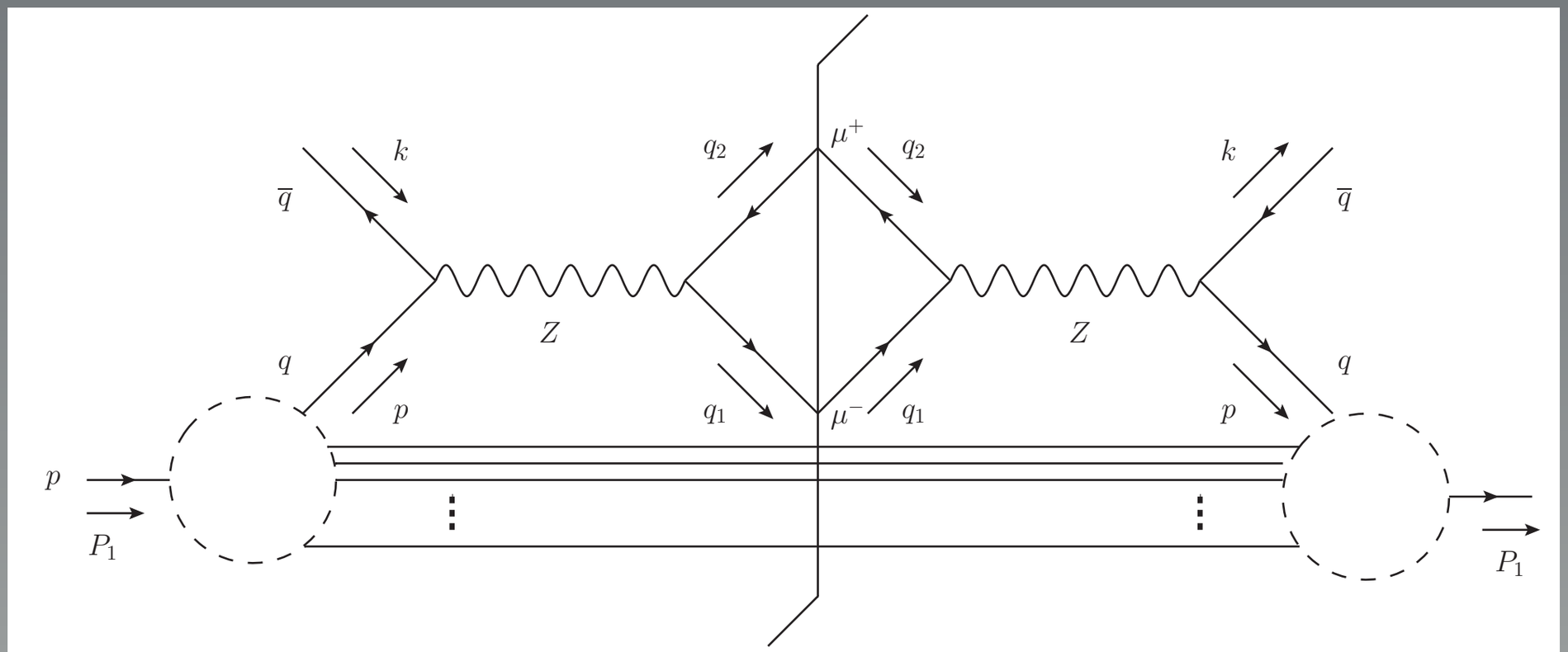
$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X}\left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$




$$\sum_X \langle P_1|\Psi|X\rangle\langle X|\overline{\Psi}|P_1\rangle$$

# PROTON-PROTON SCATTERING

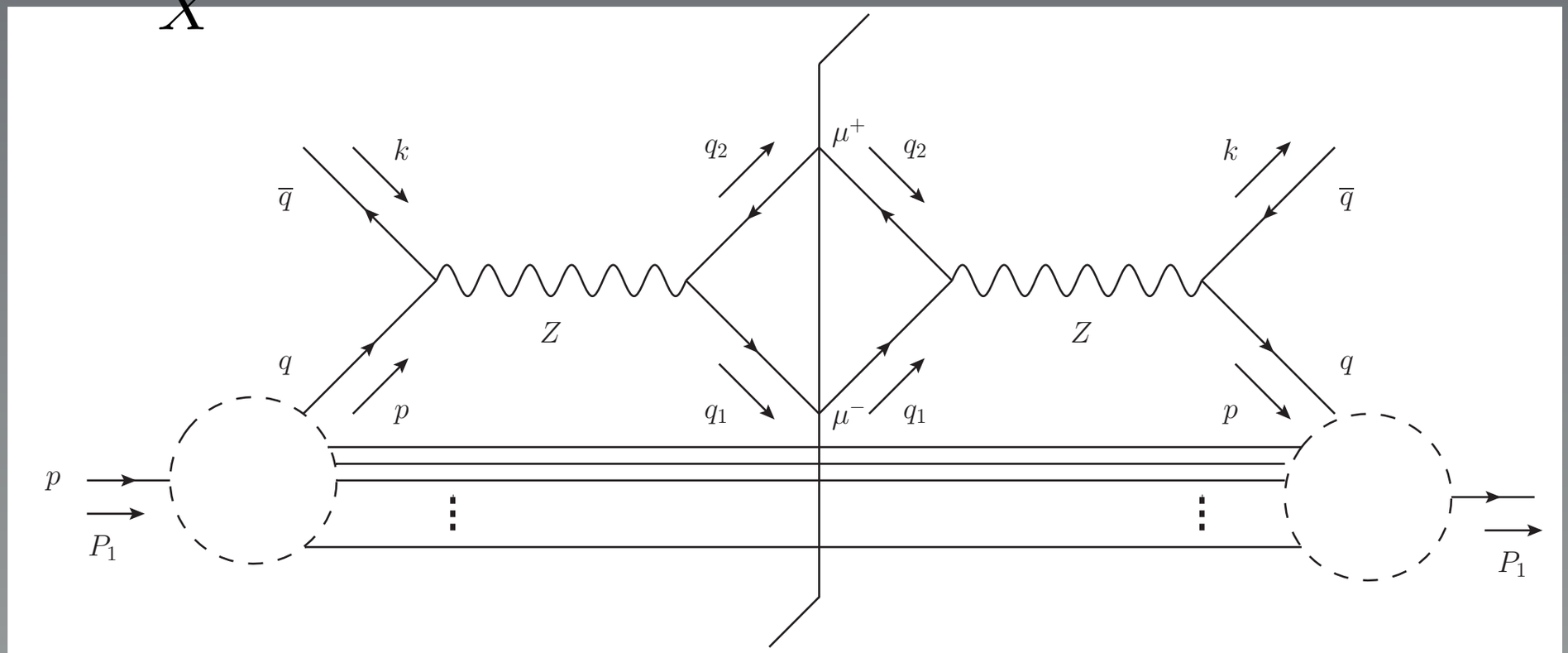
$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X}\left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$




$$\langle P_1|\Psi\sum_X|X\rangle\langle X|\overline{\Psi}|P_1\rangle$$

# PROTON-PROTON SCATTERING

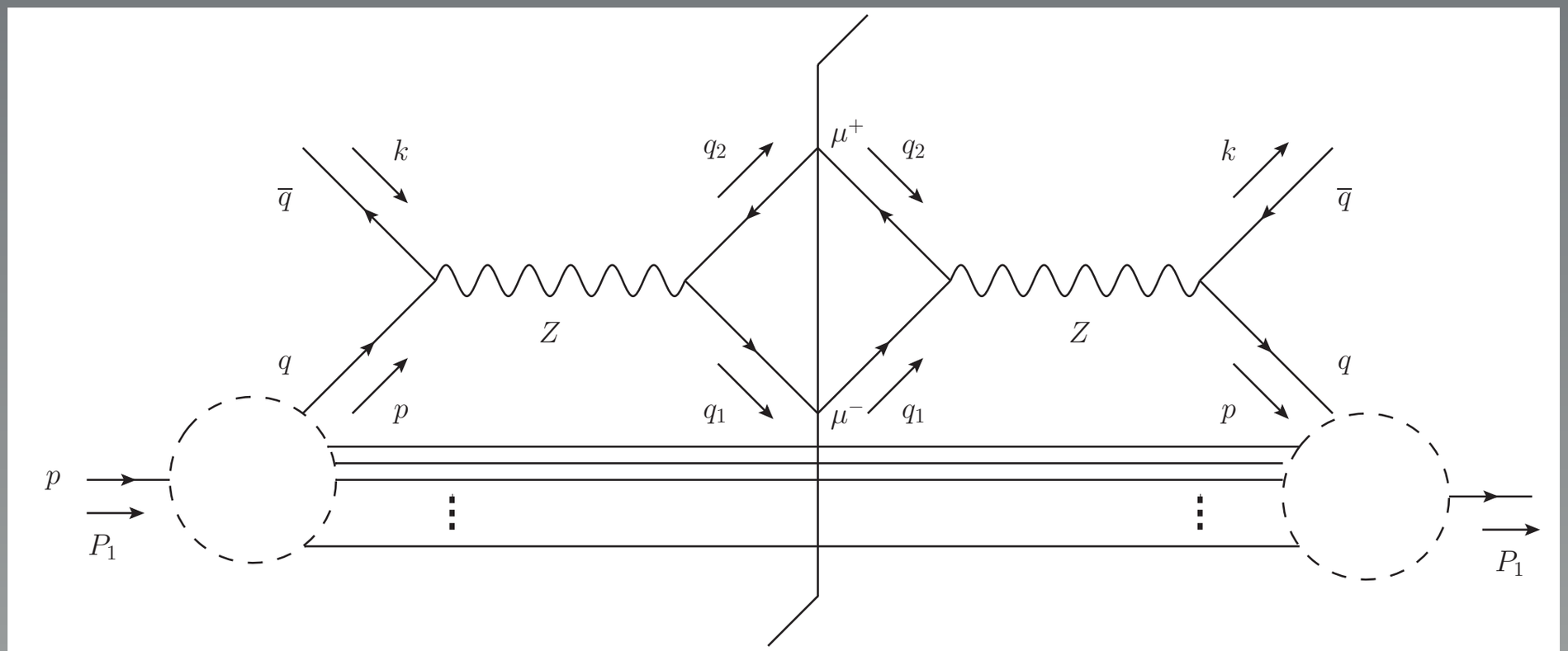
$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X}\left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$




$$\langle P_1|\Psi \underbrace{\sum_X |X\rangle\langle X|}_{1} \overline{\Psi}|P_1\rangle$$

# PROTON-PROTON SCATTERING

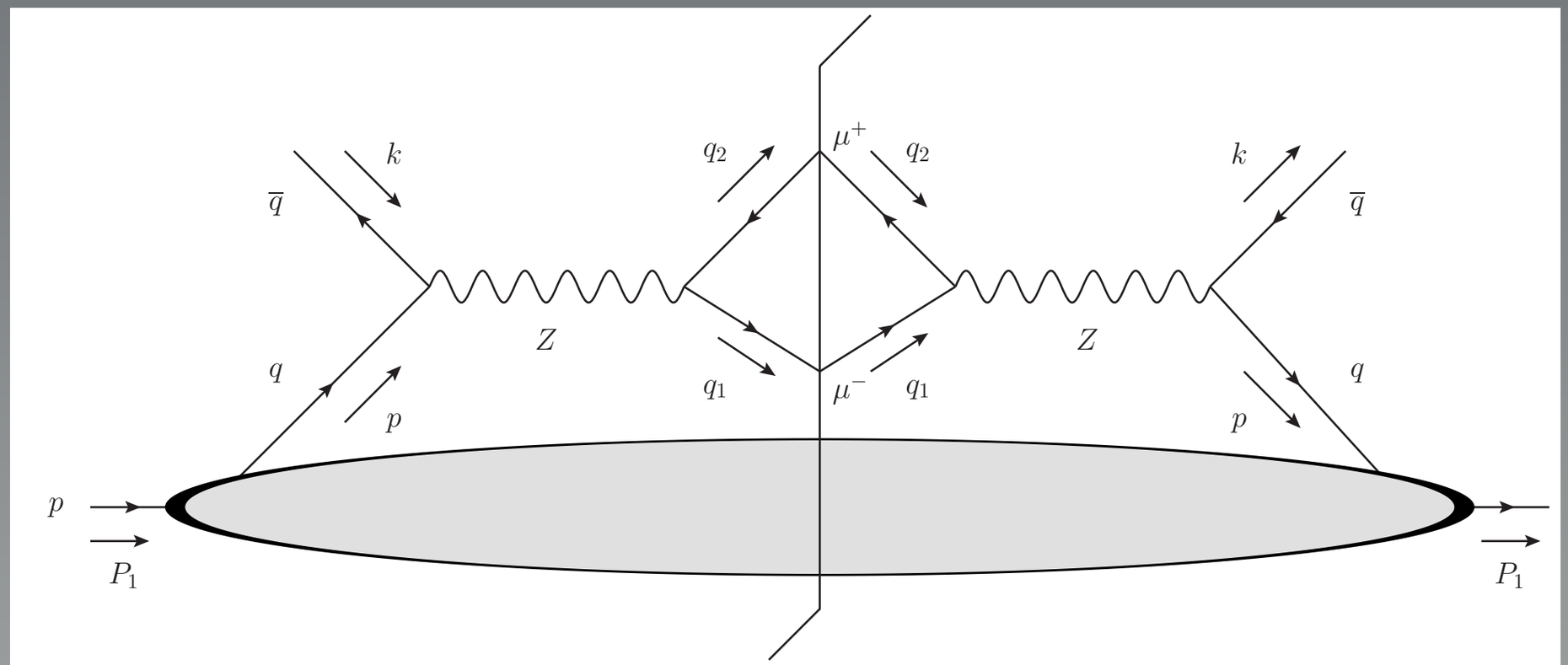
$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X} \left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$




$$\langle P_1 | \Psi \overline{\Psi} | P_1 \rangle$$

# PROTON-PROTON SCATTERING

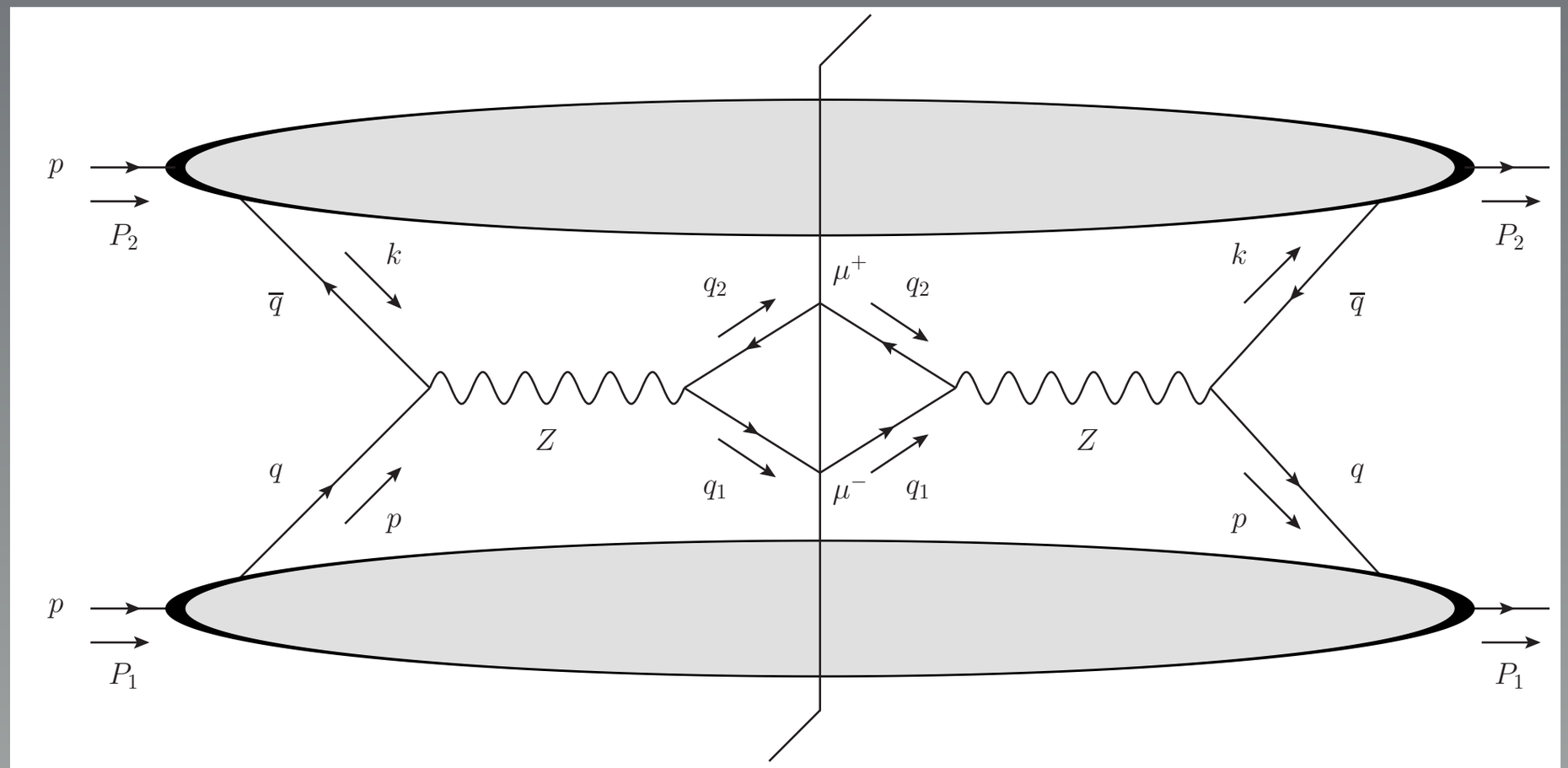
$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X}\left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$




$$\langle P_1 | \Psi\overline{\Psi} | P_1 \rangle$$

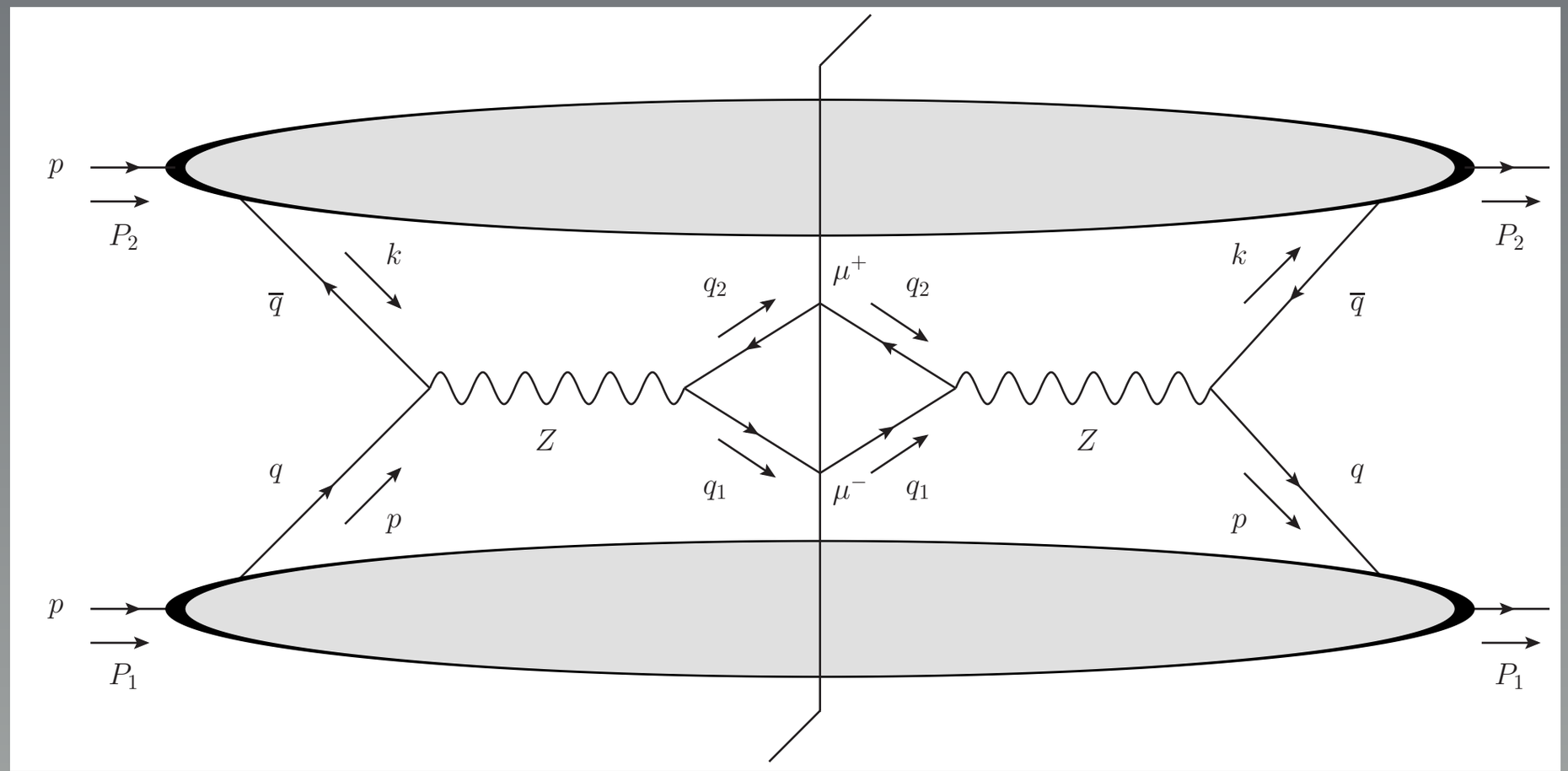
# PROTON-PROTON SCATTERING

$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X}\left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$



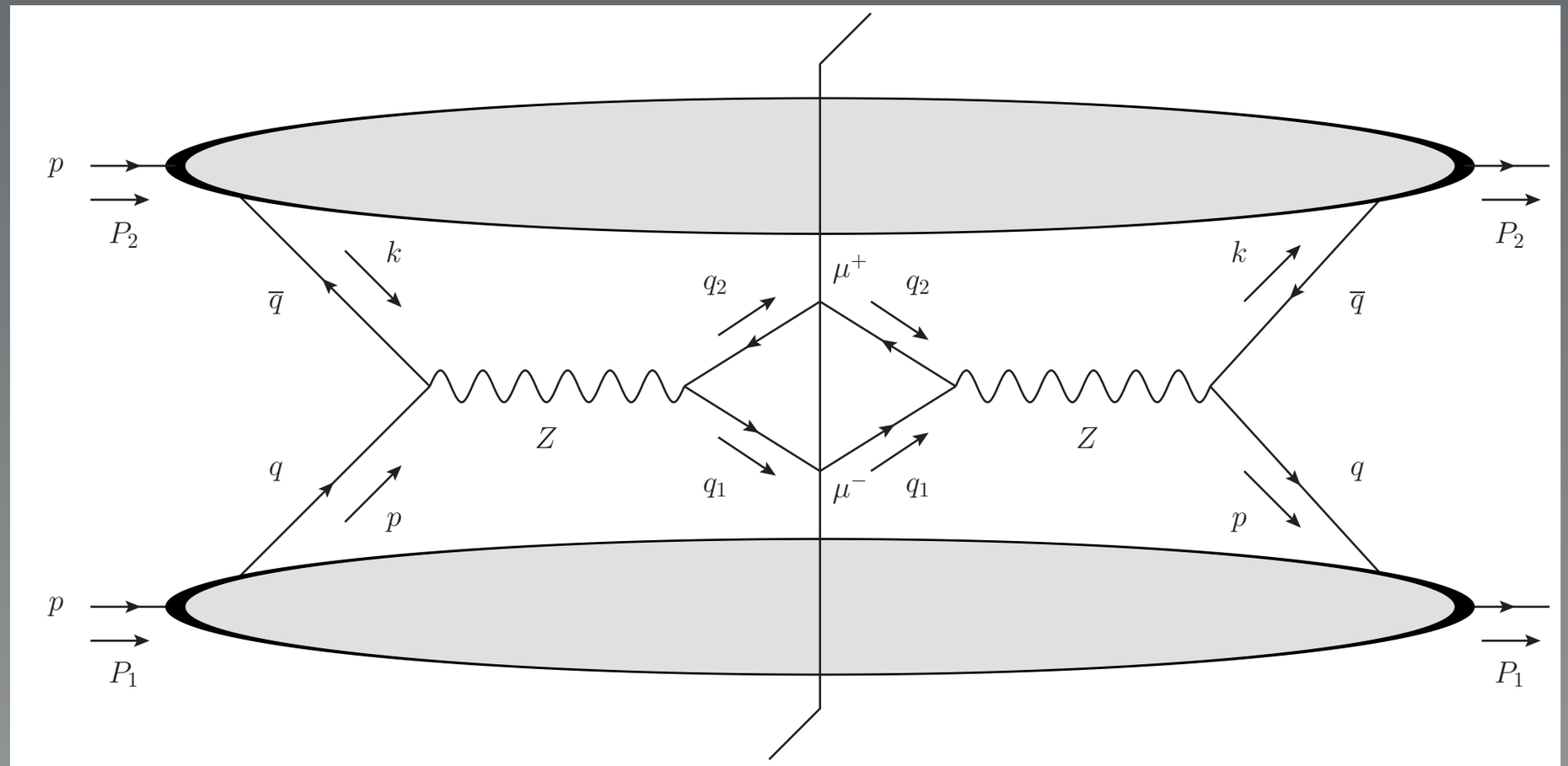
# PROTON-PROTON SCATTERING

$$\sum_X \mathcal{M}^{pp\to\mu^+\mu^- X}\left(\mathcal{M}^{pp\to\mu^+\mu^- X}\right)^* =$$



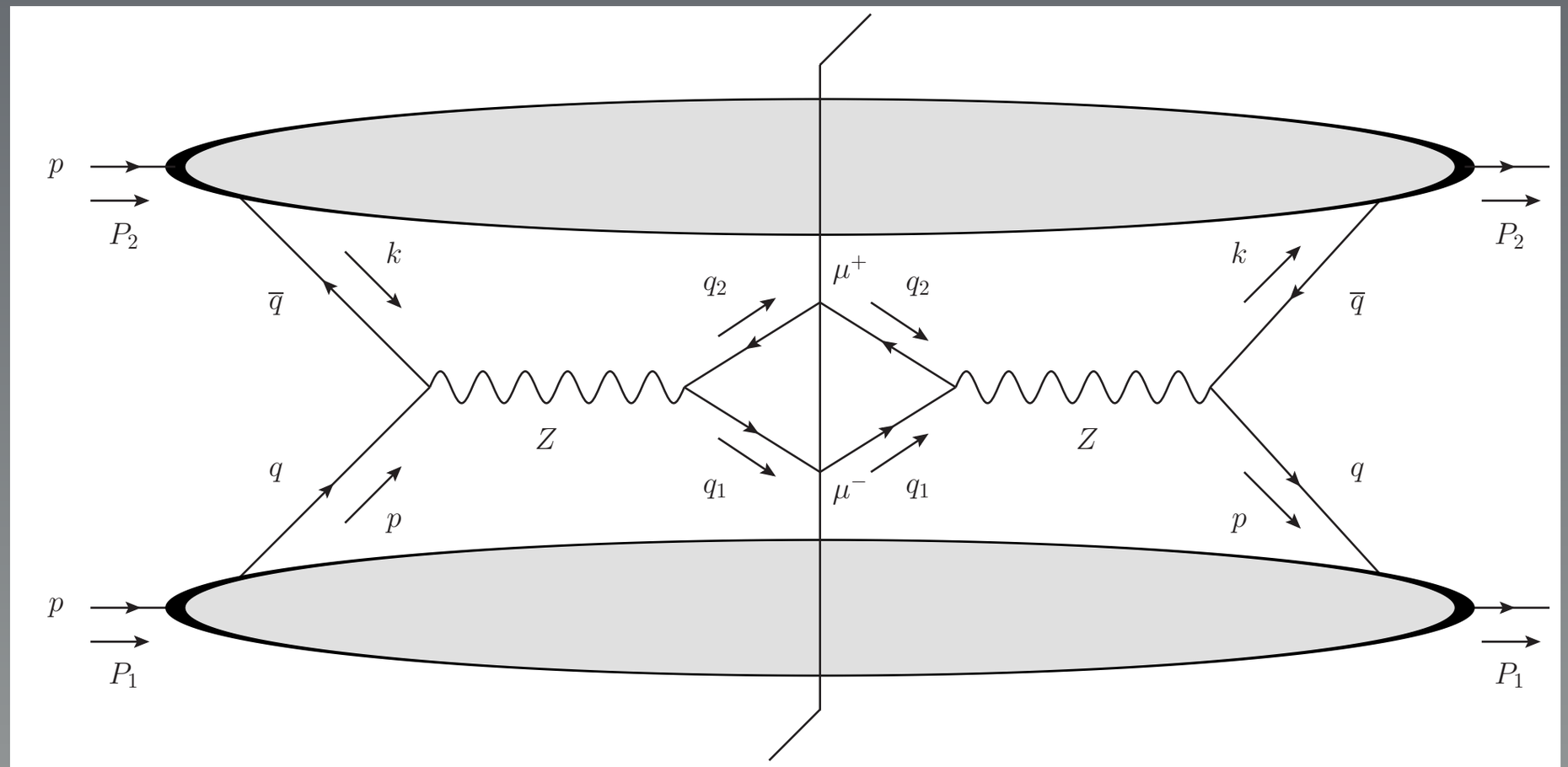

$$= \mathrm{Tr}\left[\langle P_1|\Psi\overline{\Psi}|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi\overline{\Psi}|P_2\rangle V_Z^{\mu}\right]\ldots$$

# PROTON-PROTON SCATTERING




kinematics

# PROTON-PROTON SCATTERING




$$\frac{d\sigma}{d^4q d\Omega} \propto \int d^4p\, d^4k\, \delta^4(q-p-k)\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu\,*}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

# KINEMATICAL VARIABLES

$$\frac{d\sigma}{d^4q d\Omega}$$

$$d^4q = Q\, dQ\, dY\, d^2\mathbf{q}_T$$

$$Q \equiv \sqrt{q^2} = \left(q^0\right)^2 - \mathbf{q}_T^2 - \left(q^3\right)^2$$

$$Y \equiv \frac{1}{2}\log\frac{q^0 + q^3}{q^0 - q^3} = \frac{1}{2}\log\frac{q^+}{q^-}$$

$$\mathbf{q}_T = (q^1, q^2)$$

$$q^\pm \equiv \frac{1}{\sqrt{2}}\left(q^0 \pm q^3\right)$$

# KINEMATICAL VARIABLES

$$\frac{d\sigma}{d^4q d\Omega}$$

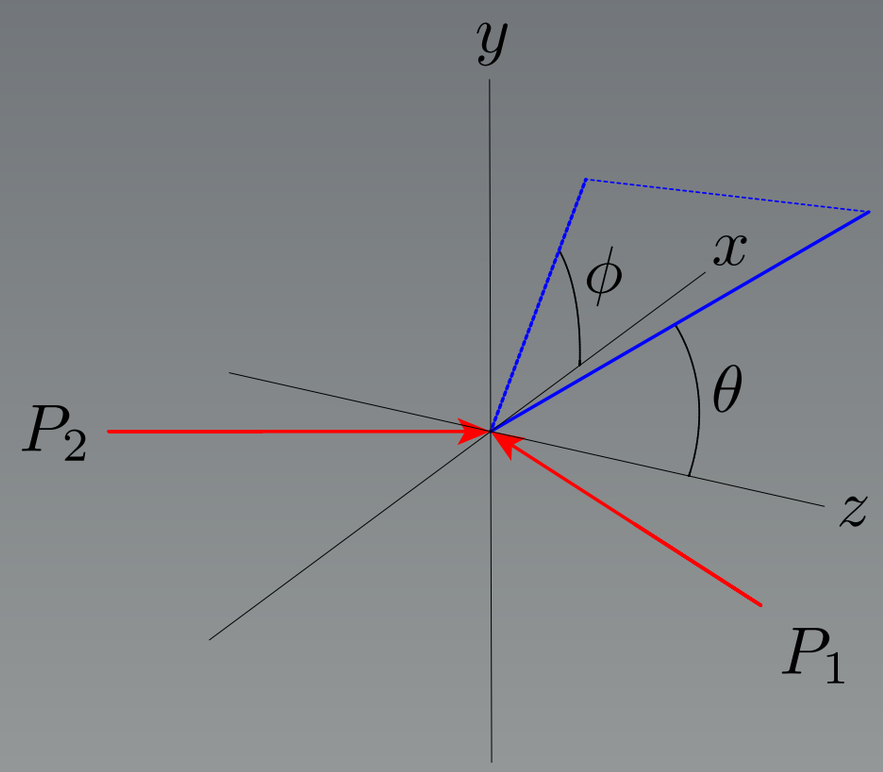
$$d^4q = Q\, dQ\, dY\, d^2\mathbf{q}_T$$

$$d\Omega = d\cos\theta d\phi$$

$$Q \equiv \sqrt{q^2} = \left(q^0\right)^2 - \mathbf{q}_T^2 - \left(q^3\right)^2$$

$$Y \equiv \frac{1}{2}\log\frac{q^0+q^3}{q^0-q^3} = \frac{1}{2}\log\frac{q^+}{q^-}$$

$$\mathbf{q}_T = (q^1, q^2)$$




Collins-Soper frame

$$q^{\pm} \equiv \frac{1}{\sqrt{2}}\left(q^0 \pm q^3\right)$$

# RAPIDITY DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY} = \int d^2\mathbf{q}_T \int d\Omega\, \frac{d\sigma}{d^4q d\Omega}$$

# RAPIDITY DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY} = \int d^2\mathbf{q}_T \int d\Omega\, \frac{d\sigma}{d^4q d\Omega}$$

$$= \int d^2\mathbf{q}_T \int d^4p\, d^4k\ \delta^4(q-p-k)\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big] \int d\Omega \ldots$$

# RAPIDITY DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY} = \int d^2\mathbf{q}_T \int d\Omega\, \frac{d\sigma}{d^4q d\Omega}$$

$$= \int d^2\mathbf{q}_T \int dp^+ dp^- d^2\mathbf{p}_T dk^+ dk^- d^2\mathbf{k}_T \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T)$$

$$\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

# RAPIDITY DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY} = \int d^2\mathbf{q}_T \int d\Omega\, \frac{d\sigma}{d^4q d\Omega}$$

$$= \int d^2\mathbf{q}_T \int dp^+ dp^- d^2\mathbf{p}_T dk^+ dk^- d^2\mathbf{k}_T \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T)$$

$$\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

$$= \int dp^+ dp^- dk^+ dk^- \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)$$

$$\mathrm{Tr}\Big[\int d^2\mathbf{p}_T \langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *} \int d^2\mathbf{k}_T \langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

# RAPIDITY DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY} = \int d^2\mathbf{q}_T \int d\Omega\, \frac{d\sigma}{d^4q d\Omega}$$

$$= \int d^2\mathbf{q}_T \int dp^+ dp^- d^2\mathbf{p}_T dk^+ dk^- d^2\mathbf{k}_T \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T)$$

$$\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

$$= \int dp^+ dp^- dk^+ dk^- \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)$$

$$\mathrm{Tr}\Big[\int d^2\mathbf{p}_T \langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *} \int d^2\mathbf{k}_T \langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

$$= \int dp^+ dk^- \delta(q^+ - p^+)\delta(q^- - k^-)$$

$$\mathrm{Tr}\Big[\int d^2\mathbf{p}_T dp^- \langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *} \int d^2\mathbf{k}_T dk^+ \langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

# RAPIDITY DISTRIBUTION

$$
\begin{aligned}
\frac{d\sigma}{dQ\,dY} &= \int d^2\mathbf{q}_T \int d\Omega\, \frac{d\sigma}{d^4q d\Omega} \\
&= \int d^2\mathbf{q}_T \int dp^+ dp^- d^2\mathbf{p}_T dk^+ dk^- d^2\mathbf{k}_T \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T) \\
&\quad \mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *} \langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots \\
&= \int dp^+ dp^- dk^+ dk^- \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-) \\
&\quad \mathrm{Tr}\Big[\int d^2\mathbf{p}_T \langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *} \int d^2\mathbf{k}_T \langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots \\
&= \int dp^+ dk^- \delta(q^+ - p^+)\delta(q^- - k^-) \\
&\quad \mathrm{Tr}\Big[\underbrace{\int d^2\mathbf{p}_T dp^- \langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle}_{\Phi_1(p^+)} V_Z^{\nu *} \underbrace{\int d^2\mathbf{k}_T dk^+ \langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle}_{\Phi_2(k^-)} V_Z^{\mu}\Big]\ldots
\end{aligned}
$$

# COLLINEAR CORRELATOR

$$\Phi^q(x) = \int d^2\mathbf{p}_T\, dp^-\, \langle P|\Psi(p)\overline{\Psi}(p)|P\rangle \qquad\qquad x \equiv p^+/P_1^+$$

?

# COLLINEAR CORRELATOR

$$\Phi^q(x) = \int d^2\mathbf{p}_T\, dp^-\, \langle P|\Psi(p)\overline{\Psi}(p)|P\rangle$$

$$\Phi^q(x) = \frac{1}{2} f_1^q(x) \not{P} + \frac{1}{2}\lambda g_1^q(x)\gamma_5 \not{P} + h_1^q(x)\gamma_5 \frac{[\not{S}_T, \not{P}]}{4} + \ldots$$

# RAPIDITY DISTRIBUTION

$$\frac{d\sigma}{dQdY} \propto f_1^q(x_1) f_1^{\bar{q}}(x_2) \ldots + (x_1 \leftrightarrow x_2)$$

# RAPIDITY DISTRIBUTION

$$\frac{d\sigma}{dQdY} \propto f_1^q(x_1) f_1^{\bar{q}}(x_2) \ldots + (x_1 \leftrightarrow x_2)$$

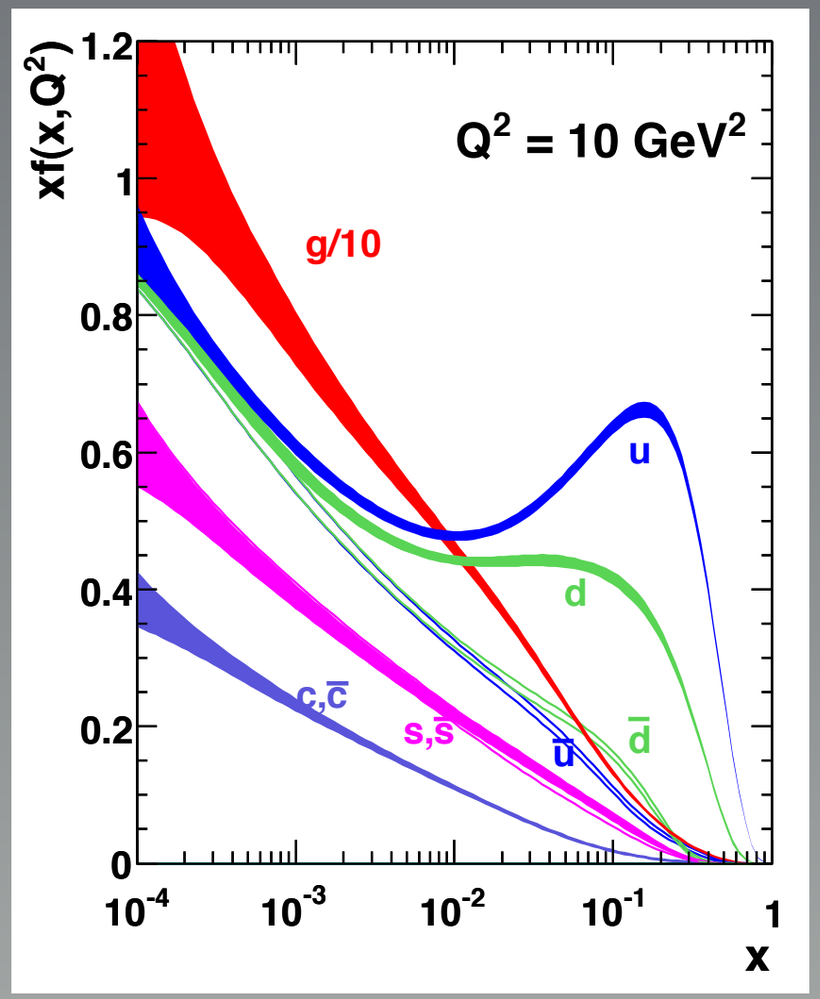
$f_1^q(x_1)$ Parton Distribution Function

# PARTON DISTRIBUTION FUNCTION

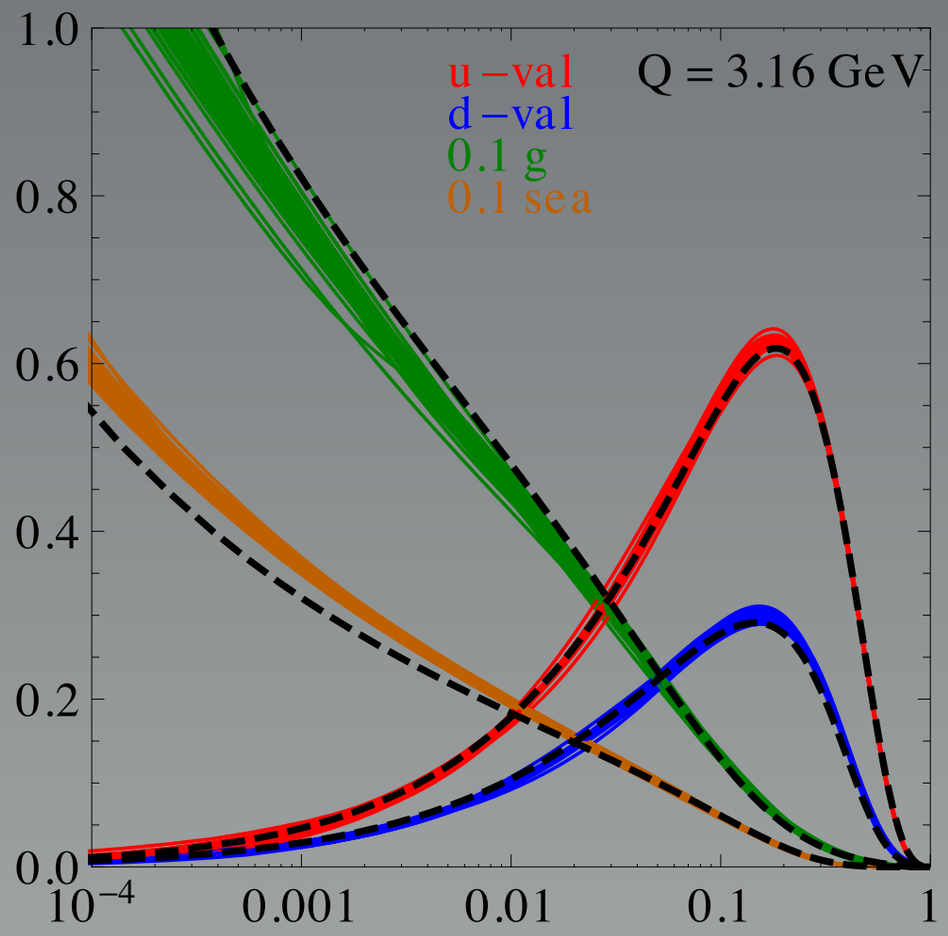
$f_1^q(x_1)$ Parton Distribution Function

# PARTON DISTRIBUTION FUNCTION

$f_1^q(x_1)$ Parton Distribution Function



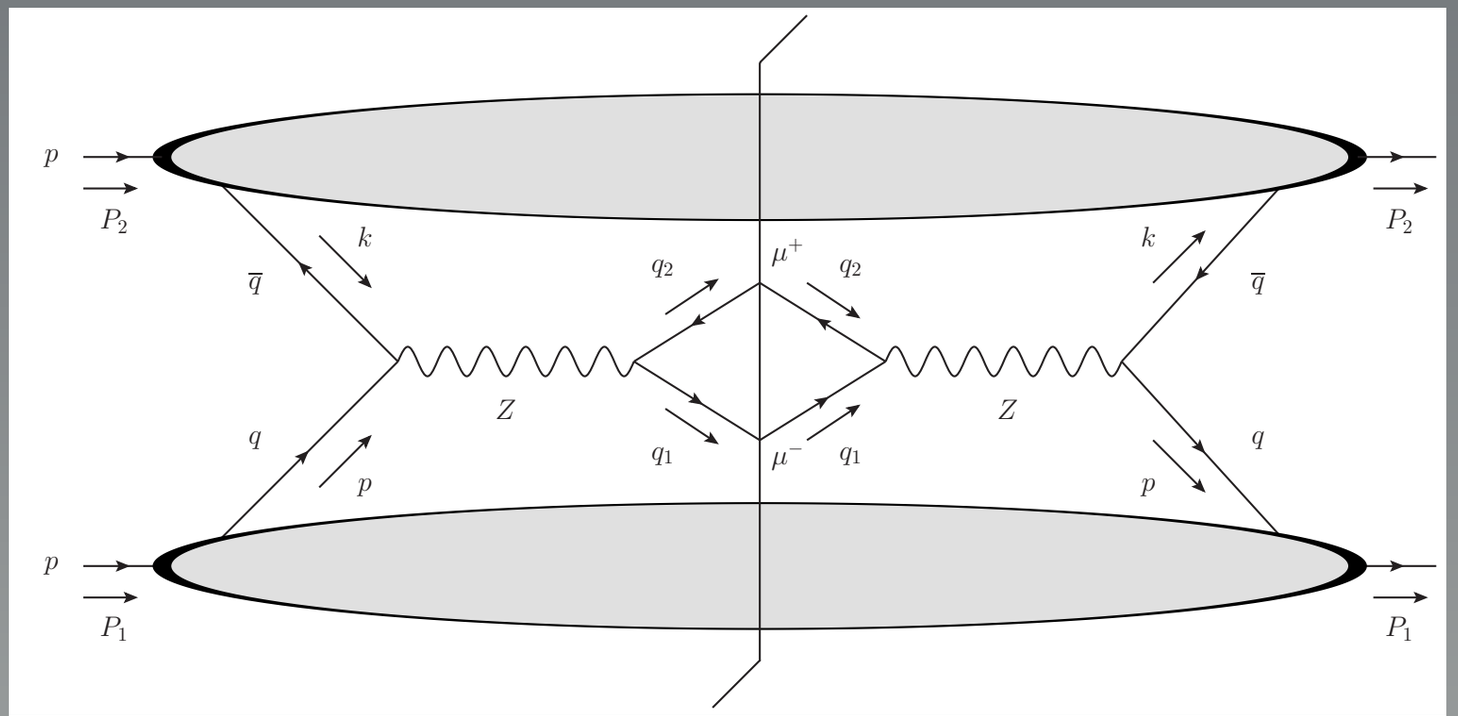

MSTW 2008




CTEQ 10

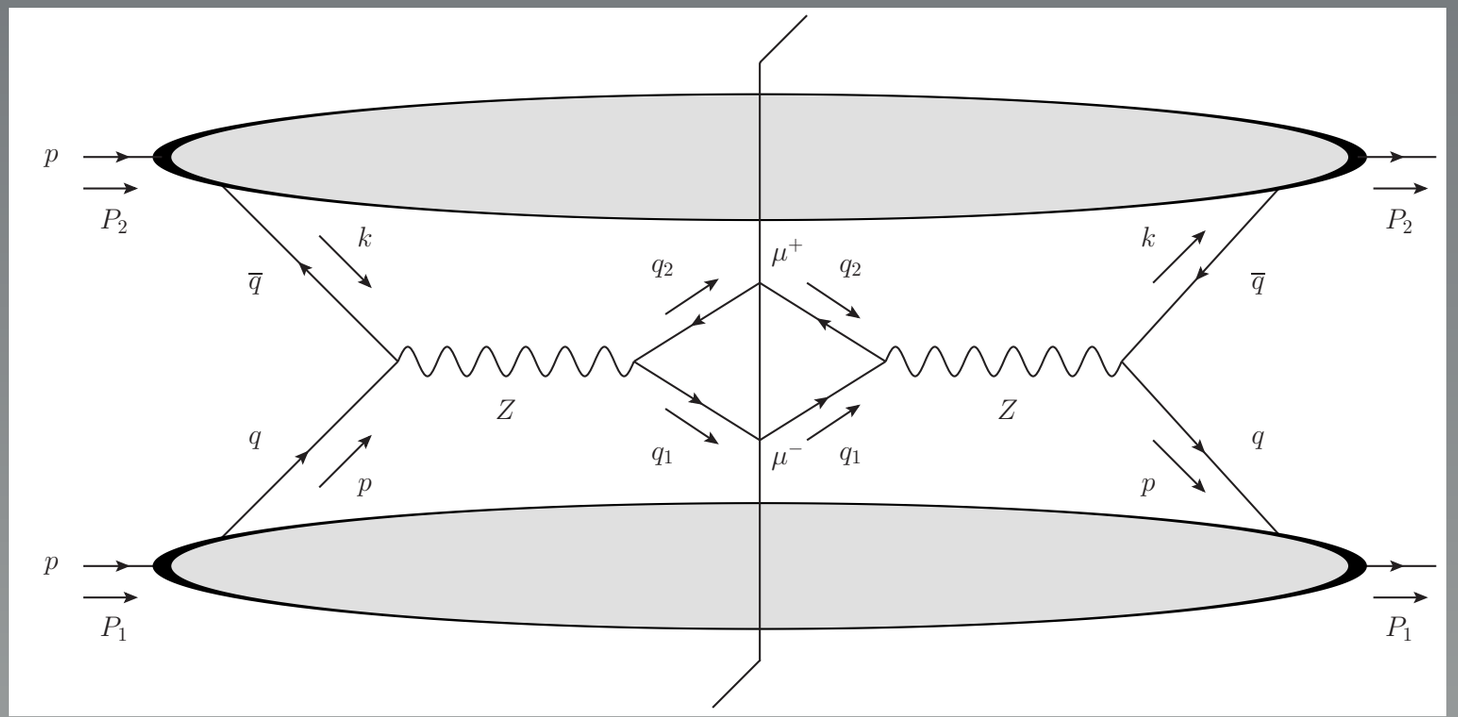
# QT DISTRIBUTION

$$\frac{d\sigma}{dQdY} \quad \Rightarrow \quad \frac{d\sigma}{dQdY\,d^2\mathbf{q}_T}$$



# QT DISTRIBUTION

$$\frac{d\sigma}{dQdY} \quad \Rightarrow \quad \frac{d\sigma}{dQdY\,d^2\mathbf{q}_T}$$




$$\frac{d\sigma}{d^4q d\Omega} \propto \int d^4p\, d^4k\, \delta^4(q-p-k)\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

# QT DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY\,d^2\mathbf{q}_T} = \int d\Omega\,\frac{d\sigma}{d^4q d\Omega}$$
$$= \int d^4p\,d^4k\;\delta^4(q-p-k)\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\int d\Omega\ldots$$

# QT DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY\,d^2\mathbf{q}_T} = \int d\Omega\,\frac{d\sigma}{d^4q d\Omega}$$

$$= \int dp^+ dp^- d^2\mathbf{p}_T dk^+ dk^- d^2\mathbf{k}_T \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T)$$

$$\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

# QT DISTRIBUTION

$$\frac{d\sigma}{dQ\,dY\,d^2\mathbf{q}_T} = \int d\Omega\,\frac{d\sigma}{d^4q d\Omega}$$

$$= \int dp^+ dp^- d^2\mathbf{p}_T dk^+ dk^- d^2\mathbf{k}_T \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T)$$

$$\mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

$$= \int dp^+ d^2\mathbf{p}_T dk^- d^2\mathbf{k}_T \delta(q^+ - p^+)\delta(q^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T)$$

$$\mathrm{Tr}\Big[\int dp^-\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\int dk^+\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots$$

# QT DISTRIBUTION

$$
\begin{aligned}
\frac{d\sigma}{dQ\,dY\,d^2\mathbf{q}_T} &= \int d\Omega\,\frac{d\sigma}{d^4q d\Omega} \\
&= \int dp^+ dp^- d^2\mathbf{p}_T dk^+ dk^- d^2\mathbf{k}_T \delta(q^+ - p^+ - k^+)\delta(q^- - p^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T) \\
&\quad \mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots \\
&= \int dp^+ d^2\mathbf{p}_T dk^- d^2\mathbf{k}_T \delta(q^+ - p^+)\delta(q^- - k^-)\delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T) \\
&\quad \mathrm{Tr}\Big[\int dp^-\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\int dk^+\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots \\
&= \int d^2\mathbf{p}_T d^2\mathbf{k}_T \delta^2(\mathbf{q}_T - \mathbf{p}_T - \mathbf{k}_T) \\
&\quad \mathrm{Tr}\Big[\int dp^-\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\int dk^+\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots
\end{aligned}
$$

# QT DISTRIBUTION

$$
\begin{aligned}
\frac{d\sigma}{dQ\,dY\,d^2\mathbf{q}_T} &= \int d\Omega\,\frac{d\sigma}{d^4q d\Omega} \\
&= \int dp^+dp^-d^2\mathbf{p}_T dk^+dk^-d^2\mathbf{k}_T \delta(q^+-p^+-k^+)\delta(q^--p^--k^-)\delta^2(\mathbf{q}_T-\mathbf{p}_T-\mathbf{k}_T) \\
&\quad \mathrm{Tr}\Big[\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots \\
&= \int dp^+d^2\mathbf{p}_T dk^-d^2\mathbf{k}_T \delta(q^+-p^+)\delta(q^--k^-)\delta^2(\mathbf{q}_T-\mathbf{p}_T-\mathbf{k}_T) \\
&\quad \mathrm{Tr}\Big[\int dp^-\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle V_Z^{\nu *}\int dk^+\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle V_Z^{\mu}\Big]\ldots \\
&= \int d^2\mathbf{p}_T d^2\mathbf{k}_T \delta^2(\mathbf{q}_T-\mathbf{p}_T-\mathbf{k}_T) \\
&\quad \mathrm{Tr}\Big[\underbrace{\int dp^-\langle P_1|\Psi(p)\overline{\Psi}(p)|P_1\rangle}_{\Phi(x_1,\mathbf{p}_T)} V_Z^{\nu *}\underbrace{\int dk^+\langle P_2|\Psi(k)\overline{\Psi}(k)|P_2\rangle}_{\Phi(x_2,\mathbf{k}_T)} V_Z^{\mu}\Big]\ldots
\end{aligned}
$$

# TMD CORRELATOR

TMD $$\Phi^q(x, \mathbf{p}_T) = \int dp^- \, \langle P|\Psi(p)\overline{\Psi}(p)|P\rangle$$

Collinear $$\Phi^q(x) = \int d^2\mathbf{p}_T \, dp^- \, \langle P|\Psi(p)\overline{\Psi}(p)|P\rangle$$

# TMD CORRELATOR

Collinear $$\Phi^q(x) = \frac{1}{2} f_1^q(x) \not{P} + \frac{1}{2} \lambda g_1^q(x) \gamma_5 \not{P} + h_1^q(x) \gamma_5 \frac{[\not{S}_T, \not{P}]}{4} + \dots$$

# TMD CORRELATOR

Collinear

$$\Phi^q(x) = \frac{1}{2} f_1^q(x) \not{P} + \frac{1}{2} \lambda g_1^q(x) \gamma_5 \not{P} + h_1^q(x) \gamma_5 \frac{[\not{S}_T, \not{P}]}{4} + \dots$$

TMD

$$\begin{aligned}
\Phi^{q[\pm]}(x, \mathbf{p}_T) = \frac{1}{2} \Bigg\{ & f_1^{q[\pm]}(x, \mathbf{p}_T^2) \not{P} + f_{1T}^{\perp q[\pm]}(x, \mathbf{p}_T^2) \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^\mu P^\nu p_T^\rho S_T^\sigma}{M} \\
& + g_{1s}^{q[\pm]}(x, \mathbf{p}_T) \gamma_5 \not{P} + h_{1T}^{q[\pm]}(x, \mathbf{p}_T^2) \frac{\gamma_5 [\not{S}_T, \not{P}]}{2} \\
& + \lambda h_{1L}^{\perp q[\pm]}(x, \mathbf{p}_T^2) \frac{\gamma_5 [\not{p}_T, \not{P}]}{2M} + h_1^{\perp q[\pm]}(x, \mathbf{p}_T^2) \frac{i [\not{p}_T, \not{P}]}{2M} \\
& + h_{1T}^{\perp q[\pm]}(x, \mathbf{p}_T^2) \left( \frac{\mathbf{p}_T \cdot \mathbf{S}_T \gamma_5 [\not{p}_T, \not{P}]}{2M^2} - \frac{\mathbf{p}_T^2 \gamma_5 [\not{S}_T, \not{P}]}{4M^2} \right) \Bigg\} + \cdots
\end{aligned}$$

# TMD CORRELATOR (UNPOLARIZED PROTON)

Collinear $$\Phi^q(x) = \frac{1}{2} f_1^q(x) \not{P} + \dots$$

TMD $$\Phi^{q[\pm]}(x, \mathbf{p}_T) = \frac{1}{2} \left\{ f_1^{q[\pm]}(x, \mathbf{p}_T^2) \not{P} + h_1^{\perp q[\pm]}(x, \mathbf{p}_T^2) \frac{i[\not{p}_T, \not{P}]}{2M} \right\} + \cdots$$

# COLLINEAR VS TMD

- 3 distributions per parton
- PDF
- Helicity
- Transversity
- PDFs well known, Helicity well known (DSSV), Transversity known

- 8 distributions per parton
- TMD PDF + BM function
- Helicity + Worm-Gear
- Sivers + Worm-Gear +Transversity + Pretzelosity
- Only some information on quark TMD PDF, BM and Sivers function

# GLUONS

Collinear

$$\Phi_g^{\mu\nu}(x) = \frac{1}{2x}\Big\{ - g_T^{\mu\nu}\, f_1^g(x) + i\epsilon_T^{\mu\nu}\,\lambda\, g_{1L}^g(x)\Big\} + \dots$$

TMD

$$\begin{aligned}\Phi_g^{\mu\nu}(x,\mathbf{p}_T) = \frac{1}{2x}\Big\{ & - g_T^{\mu\nu}\, f_1^g(x,\mathbf{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M^2} + g_T^{\mu\nu}\,\frac{\mathbf{p}_T^2}{2M^2}\right) h_1^{\perp g}(x,\mathbf{p}_T^2) \\ & + i\epsilon_T^{\mu\nu}\,\frac{\mathbf{p}_T\cdot\mathbf{S}_T}{M}\, g_{1T}^g(x,\mathbf{p}_T^2) + g_T^{\mu\nu}\,\frac{\epsilon_T^{p_T S_T}}{M}\, f_{1T}^{\perp g}(x,\mathbf{p}_T^2) \\ & - \frac{\epsilon_T^{p_T\{\mu} S_T^{\nu\}} + \epsilon_T^{S_T\{\mu} p_T^{\nu\}}}{4M}\, h_{1T}^g(x,\mathbf{p}_T^2) - \frac{\epsilon_T^{p_T\{\mu} p_T^{\nu\}}}{2M^2}\, h_{1L}^{\perp g}(x,\mathbf{p}_T^2) \\ & - \frac{\epsilon_T^{p_T\{\mu} p_T^{\nu\}}}{2M^2}\,\frac{\mathbf{p}_T\cdot\mathbf{S}_T}{M}\, h_{1T}^{\perp g}(x,\mathbf{p}_T^2) + i\epsilon_T^{\mu\nu}\,\lambda\, g_{1L}^g(x,\mathbf{p}_T^2)\Big\} + \dots\end{aligned}$$

# GLUONS (UNPOL. PROTON)

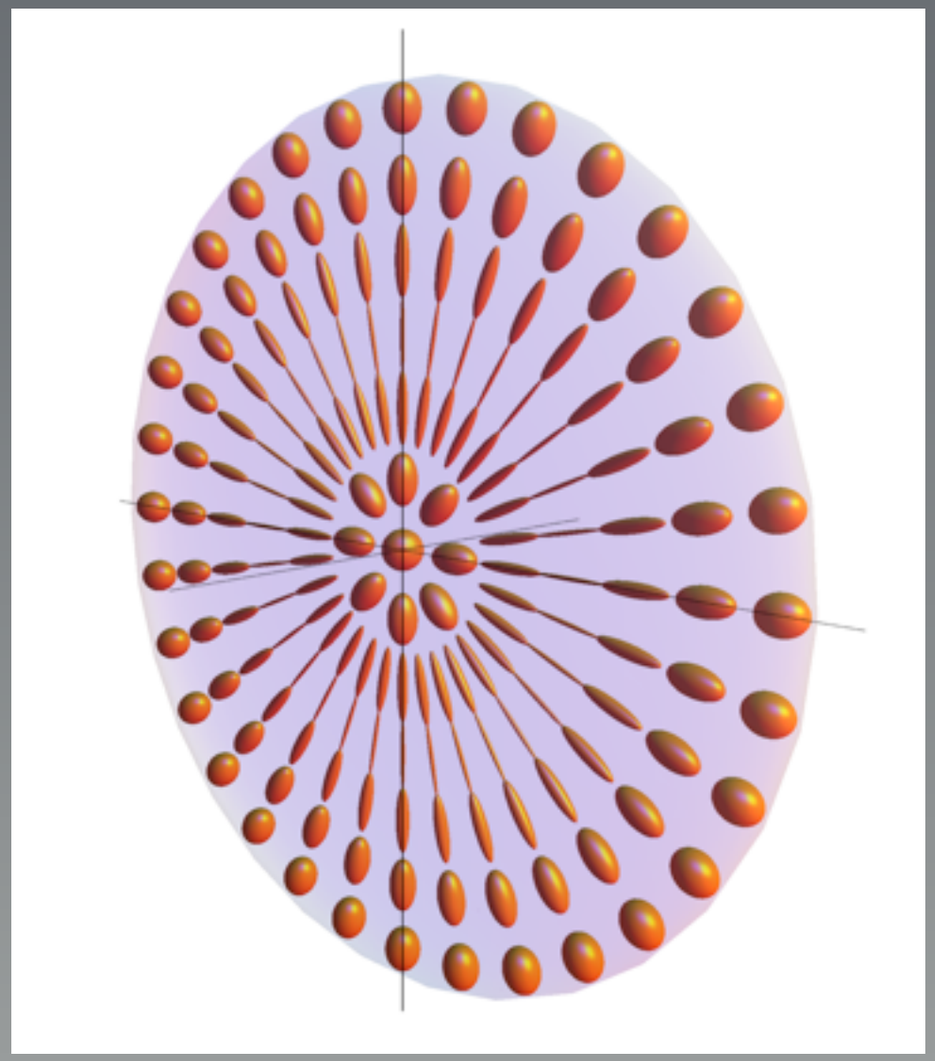
Collinear

$$\Phi_g^{\mu\nu}(x) = -\frac{1}{2x} g_T^{\mu\nu} f_1^g(x) + \dots$$

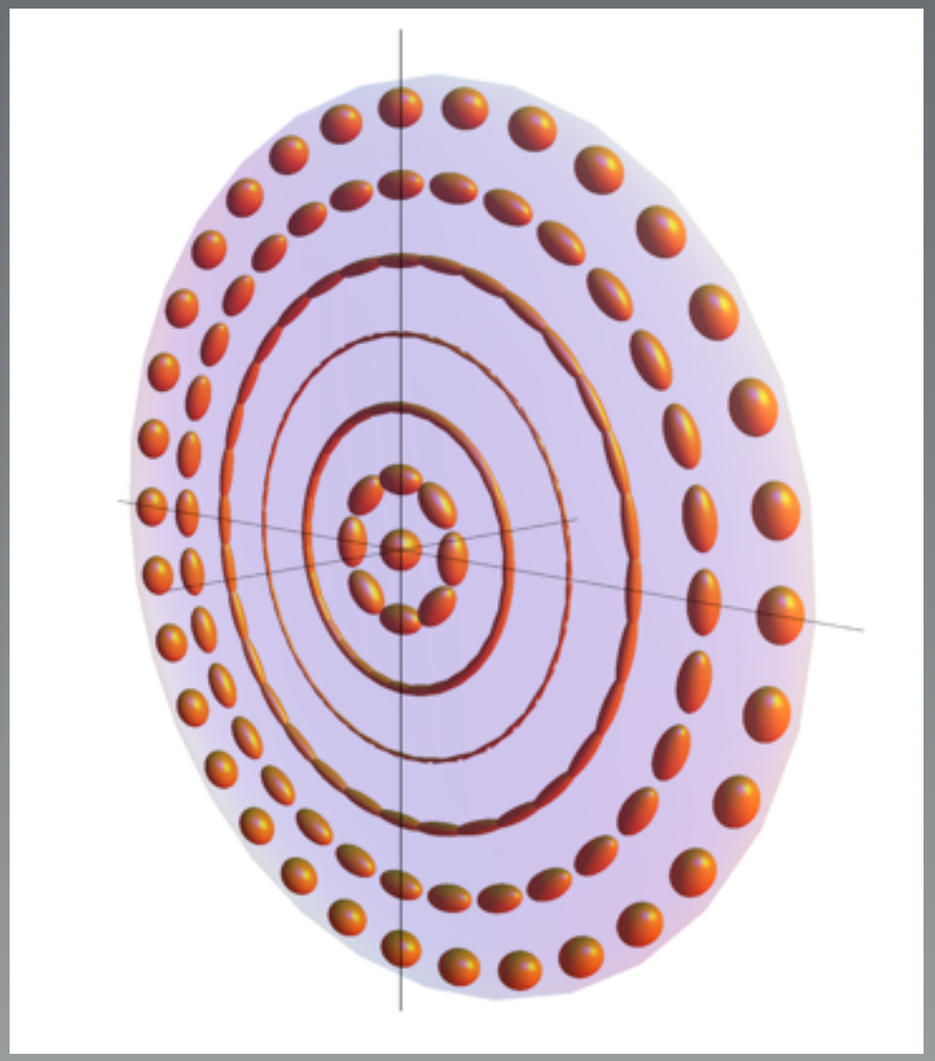
TMD

$$\Phi_g^{\mu\nu}(x, \mathbf{p}_T) = \frac{1}{2x}\left\{ - g_T^{\mu\nu} f_1^g(x, \mathbf{p}_T^2) + \left( \frac{p_T^\mu p_T^\nu}{M^2} + g_T^{\mu\nu} \frac{\mathbf{p}_T^2}{2M^2} \right) h_1^{\perp g}(x, \mathbf{p}_T^2) \right\} + \dots$$

# LINEARLY POLARIZED GLUON DISTRIBUTION

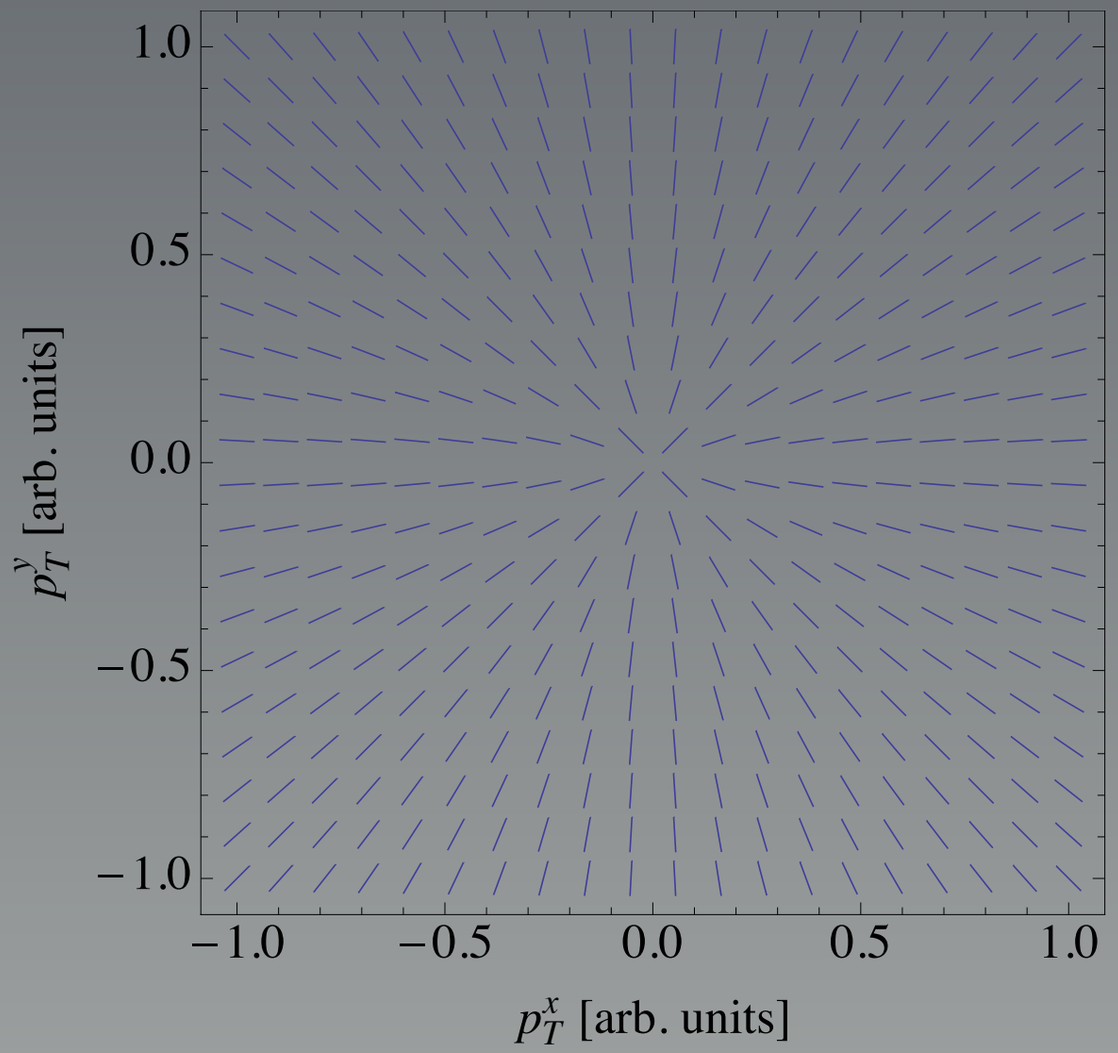


$h_1^{\perp g} > 0$

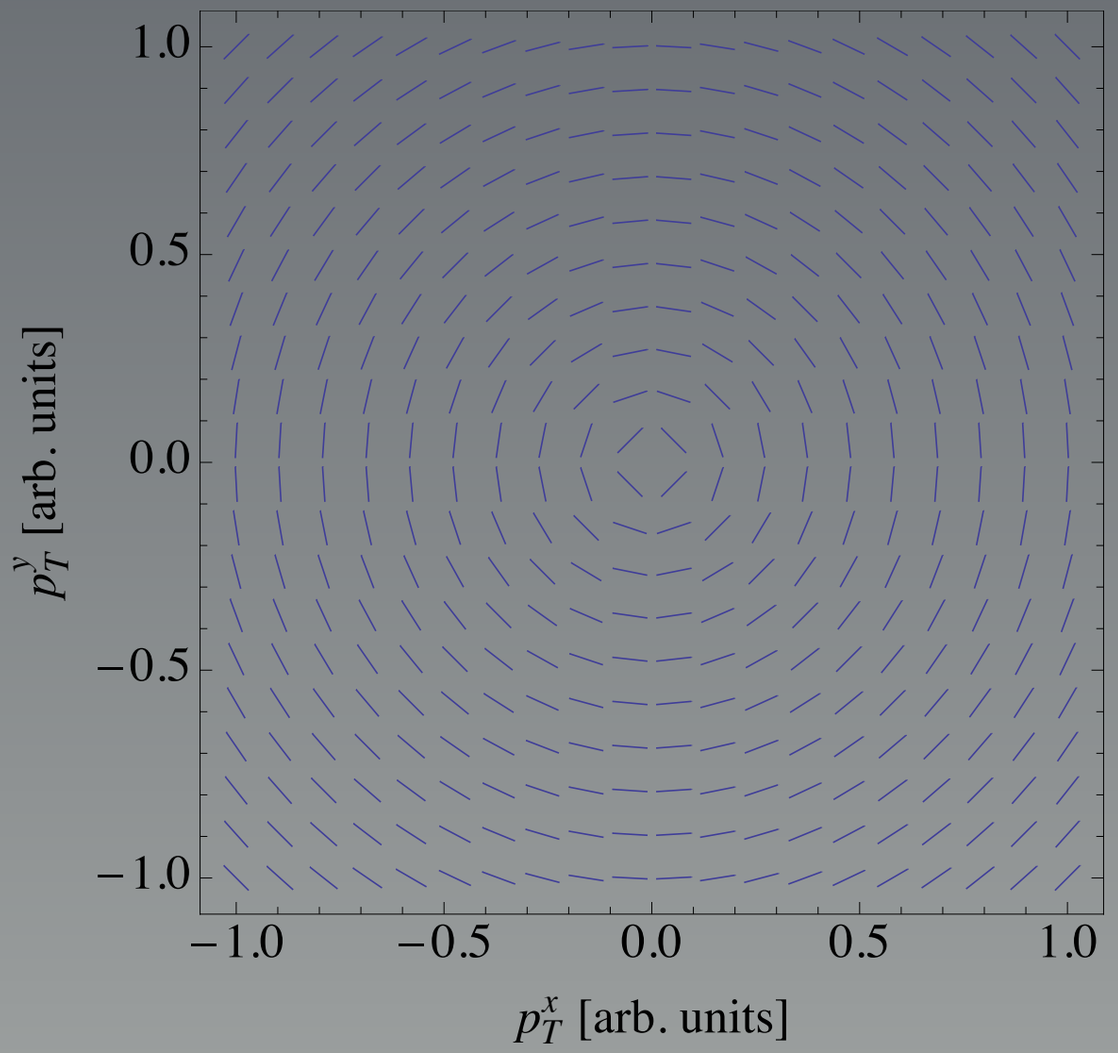


$h_1^{\perp g} < 0$

# LINEARLY POLARIZED GLUON DISTRIBUTION




$h_1^{\perp g} > 0$



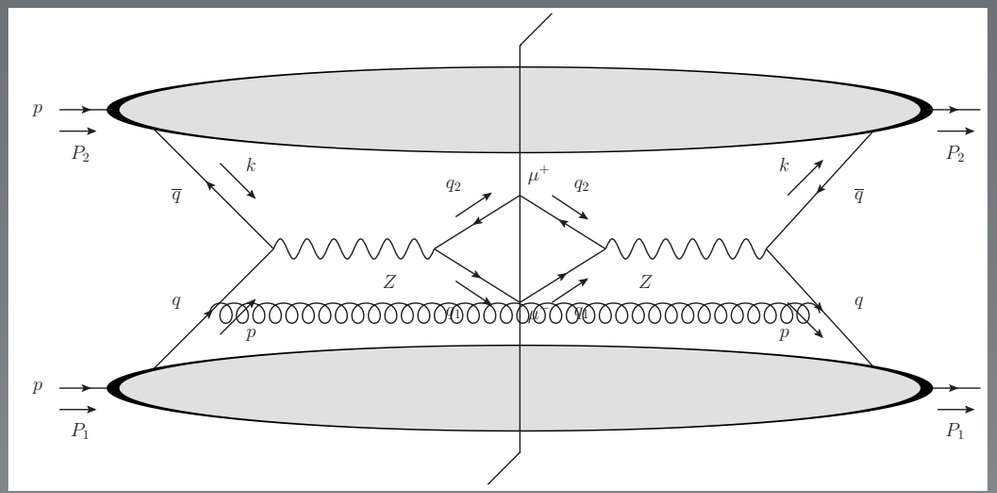

$h_1^{\perp g} < 0$

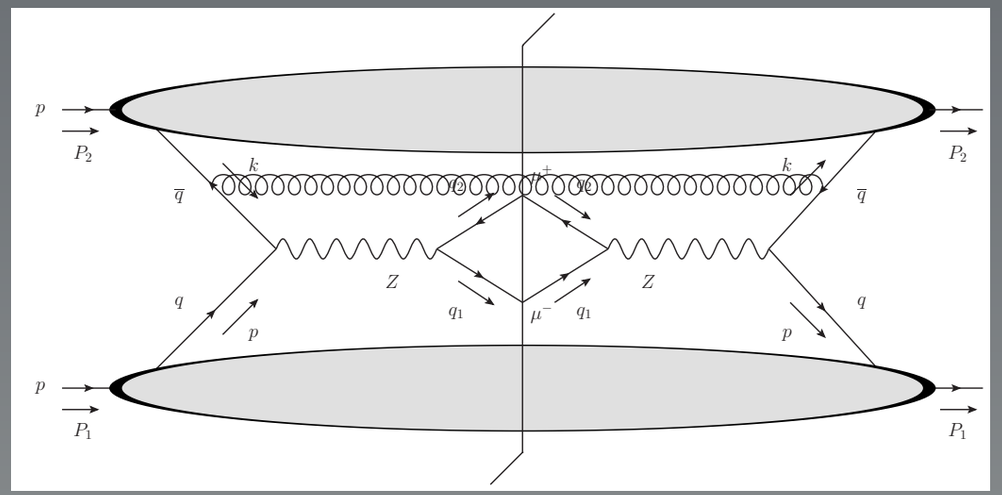
# OTHER DIFFERENCES & COMPLICATIONS

Quantum corrections

# OTHER DIFFERENCES & COMPLICATIONS

## Quantum corrections

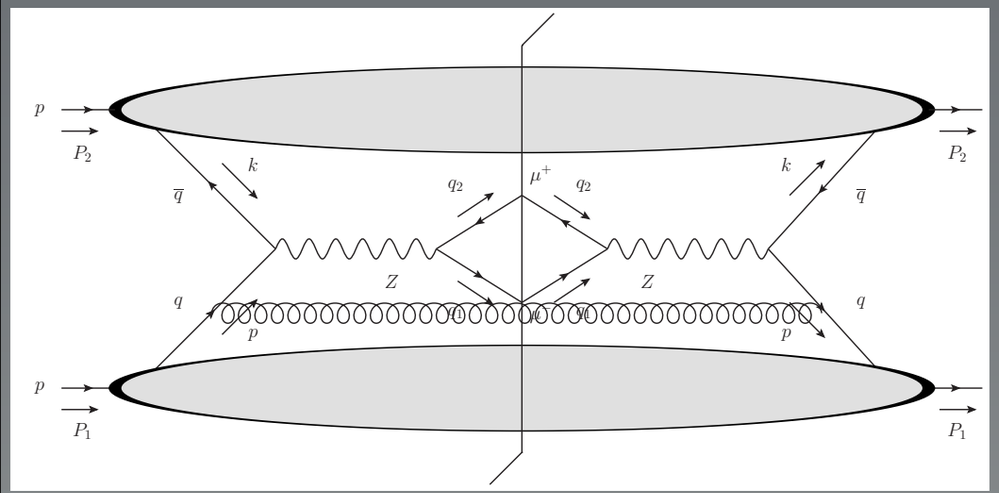


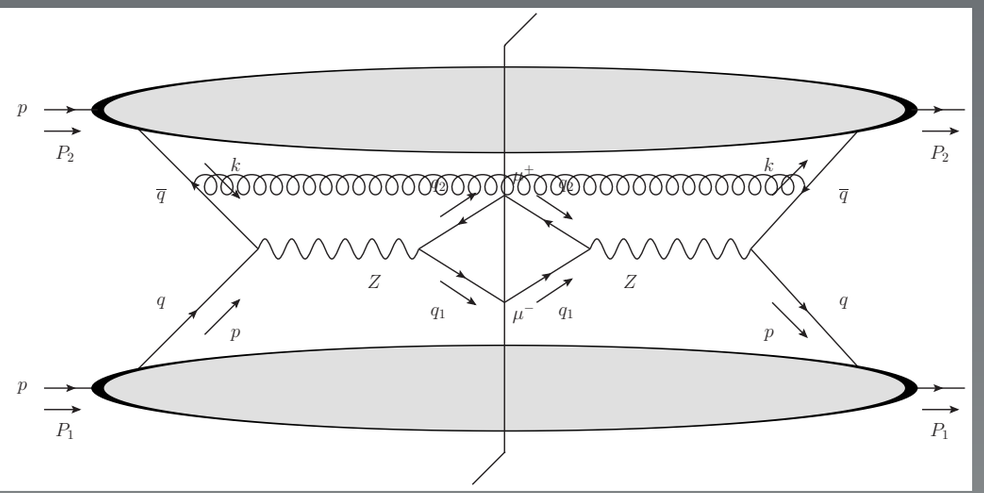




## Evolution (in μ)

# OTHER DIFFERENCES & COMPLICATIONS

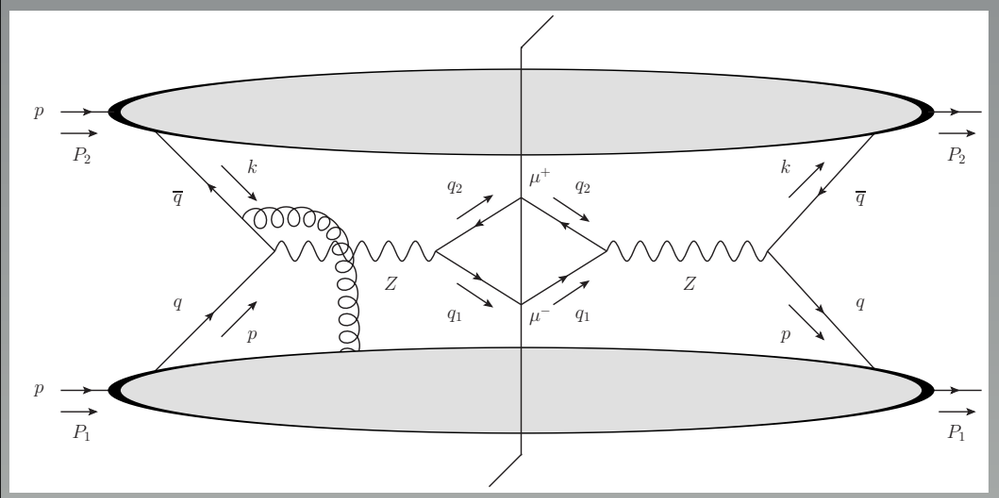
## Quantum corrections

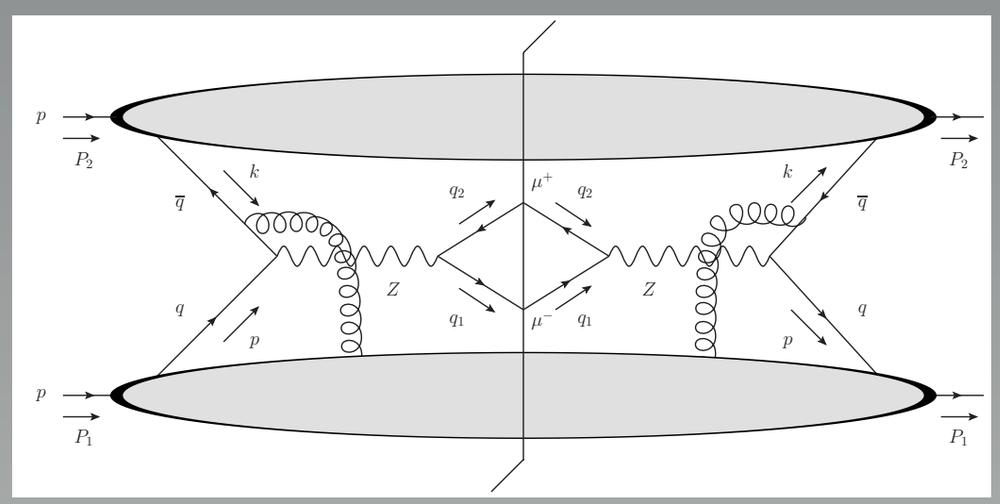



Evolution (in μ)

## Gauge link



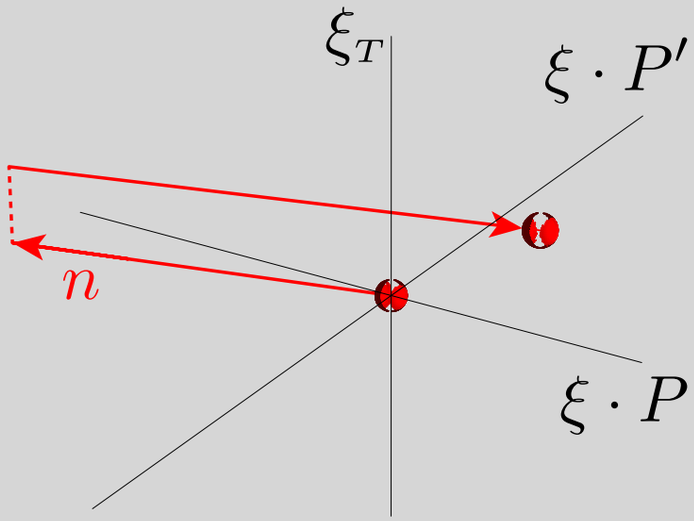




-Evol. in ζ
-Process dependence
-Non factorization

# OTHER DIFFERENCES & COMPLICATIONS

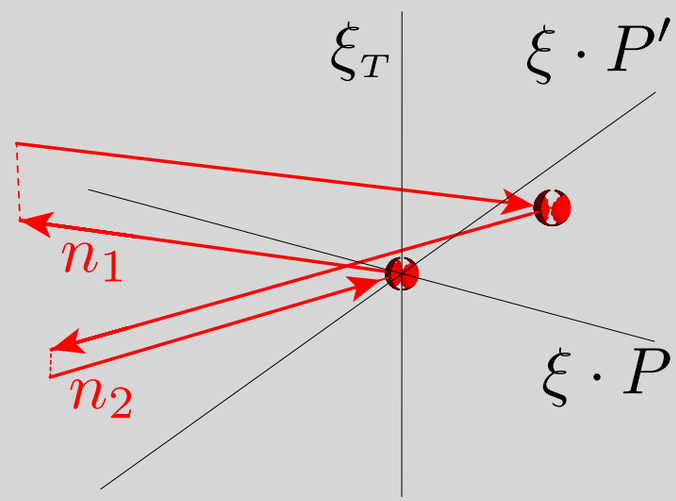
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} \propto \int \mathrm{d}^2\boldsymbol{p}_T \mathrm{d}^2\boldsymbol{k}_T \mathrm{d}^2\boldsymbol{\ell}_T \delta^2(\boldsymbol{p}_T + \boldsymbol{k}_T + \boldsymbol{\ell}_T - \boldsymbol{q}_T) H_{\mu\rho\nu\sigma} S(\boldsymbol{\ell}_T, \mu, \rho)\, \mathrm{F.T.}\left[\frac{\Phi_g^{\mu\nu}(x_1, \xi_{1T}, \zeta_1, \mu)}{S(\xi_{1T}, \mu, \rho)}\right] \times \mathrm{F.T.}\left[\frac{\Phi_g^{\rho\sigma}(x_2, \xi_{2T}, \zeta_2, \mu)}{S(\xi_{2T}, \mu, \rho)}\right]$$

$$\Phi_g^{\mu\nu}(x, \boldsymbol{p}_T, \zeta, \mu) \propto \mathrm{F.T.}\left[\langle P| F^{n\nu}(0)\, \mathcal{U}^{n[-]}_{[0,\xi]}\, F^{n\mu}(\xi)\, \mathcal{U}^{n[-]}_{[\xi,0]} |P\rangle\right]$$




$$\zeta_i^2 \equiv \frac{(2\, n_i \cdot P_i)^2}{n_i^2}$$

$$S(\xi_T, \mu, \rho) \propto \langle 0| \mathcal{U}^{n_1[-]}_{[\xi_T,0]}\, \mathcal{U}^{n_2[-]}_{[0,\xi_T]} |0\rangle$$




$$\rho^2 \equiv \frac{(2n_1 \cdot n_2)^2}{n_1^2 n_2^2} = \left(\frac{\zeta_1\zeta_2}{s} + \frac{s}{\zeta_1\zeta_2}\right)^2$$

# OTHER DIFFERENCES & COMPLICATIONS

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} \propto \int \mathrm{d}^2\boldsymbol{p}_T \mathrm{d}^2\boldsymbol{k}_T \mathrm{d}^2\boldsymbol{\ell}_T \delta^2(\boldsymbol{p}_T + \boldsymbol{k}_T + \boldsymbol{\ell}_T - \boldsymbol{q}_T) H_{\mu\rho\nu\sigma} S(\boldsymbol{\ell}_T, \mu, \rho)\, \mathrm{F.T.}\left[\frac{\Phi_g^{\mu\nu}(x_1, \xi_{1T}, \zeta_1, \mu)}{S(\xi_{1T}, \mu, \rho)}\right] \times \mathrm{F.T.}\left[\frac{\Phi_g^{\rho\sigma}(x_2, \xi_{2T}, \zeta_2, \mu)}{S(\xi_{2T}, \mu, \rho)}\right]$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} \propto \int \mathrm{d}^2\boldsymbol{p}_T \mathrm{d}^2\boldsymbol{k}_T \delta^2(\boldsymbol{p}_T + \boldsymbol{k}_T - \boldsymbol{q}_T) \mathcal{M}_{\mu\rho\kappa\lambda} \left(\mathcal{M}_{\nu\sigma}{}^{\kappa\lambda}\right)^* \Phi_g^{\mu\nu}(x_1, \boldsymbol{p}_T, \zeta_1, \mu)\, \Phi_g^{\rho\sigma}(x_2, \boldsymbol{k}_T, \zeta_2, \mu),$$

$$\text{with} \quad \zeta_1 = \zeta_2 \simeq 1.5\sqrt{s}$$

$$\Phi_g^{\mu\nu}(x, \mathbf{p}_T, \zeta, \mu) \equiv \int \frac{d(\xi\cdot P)\, d^2\xi_T}{(xP\cdot n)^2(2\pi)^3} e^{i(xP+p_T)\cdot\xi} \left\langle P|F_a^{n\nu}(0) \left(\mathcal{U}_{[0,\xi]}^{n[-]}\right)_{ab} F_b^{n\mu}(\xi)|P\right\rangle\Big|_{\xi\cdot P'=0}$$

# OUTLINE

- Intro TMD factorization
- **Calculation of TMDs**
- TMD effects in Higgs production
- How to measure the gluon TMDs

# CALCULATION OF THE GLUON TMDS

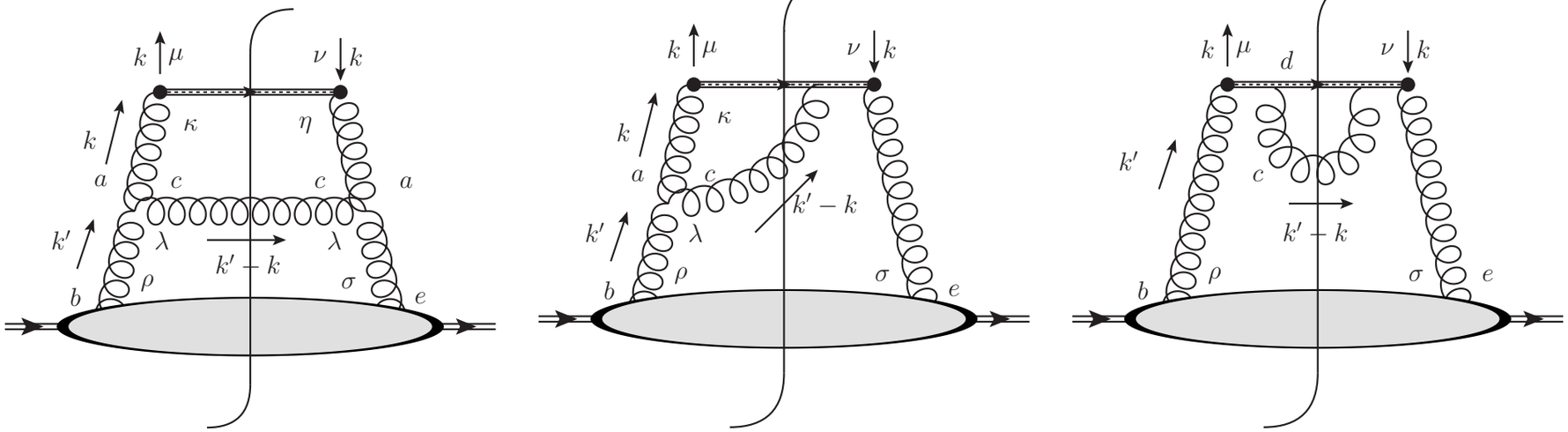
$$\Phi_g^{\mu\nu}(x,\mathbf{p}_T,\zeta,\mu) \equiv \int \frac{d(\xi\cdot P)\,d^2\xi_T}{(xP\cdot n)^2(2\pi)^3} e^{i(xP+p_T)\cdot\xi} \left\langle P|F_a^{n\nu}(0)\left(\mathcal{U}_{[0,\xi]}^{n[-]}\right)_{ab} F_b^{n\mu}(\xi)|P\right\rangle\Big|_{\xi\cdot P'=0}$$

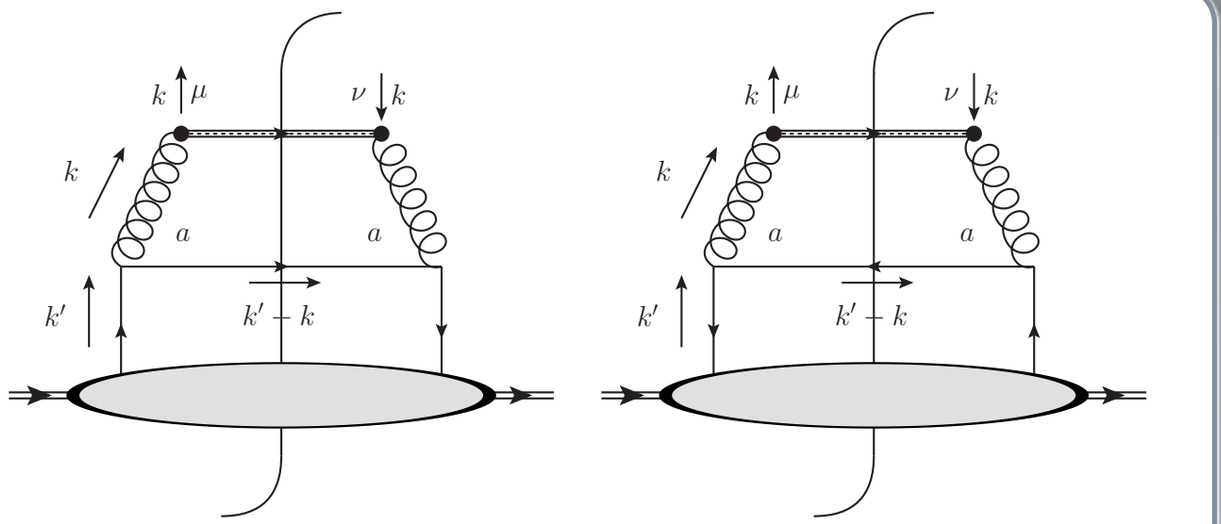
# CALCULATION OF THE GLUON TMDS

$$\Phi_g^{\mu\nu}(x,\mathbf{p}_T,\zeta,\mu) \equiv \int \frac{d(\xi\cdot P)\,d^2\xi_T}{(xP\cdot n)^2(2\pi)^3} e^{i(xP+p_T)\cdot\xi} \left\langle P|F_a^{n\nu}(0)\left(\mathcal{U}_{[0,\xi]}^{n[-]}\right)_{ab} F_b^{n\mu}(\xi)|P\right\rangle\Big|_{\xi\cdot P'=0}$$

- Ordinary pQCD can be used to calculate the large pT tail of the correlator

# TAIL OF THE GLUON CORRELATOR



# TAIL OF THE GLUON CORRELATOR

in $\zeta \to \infty$ limit, results compatible with the literature

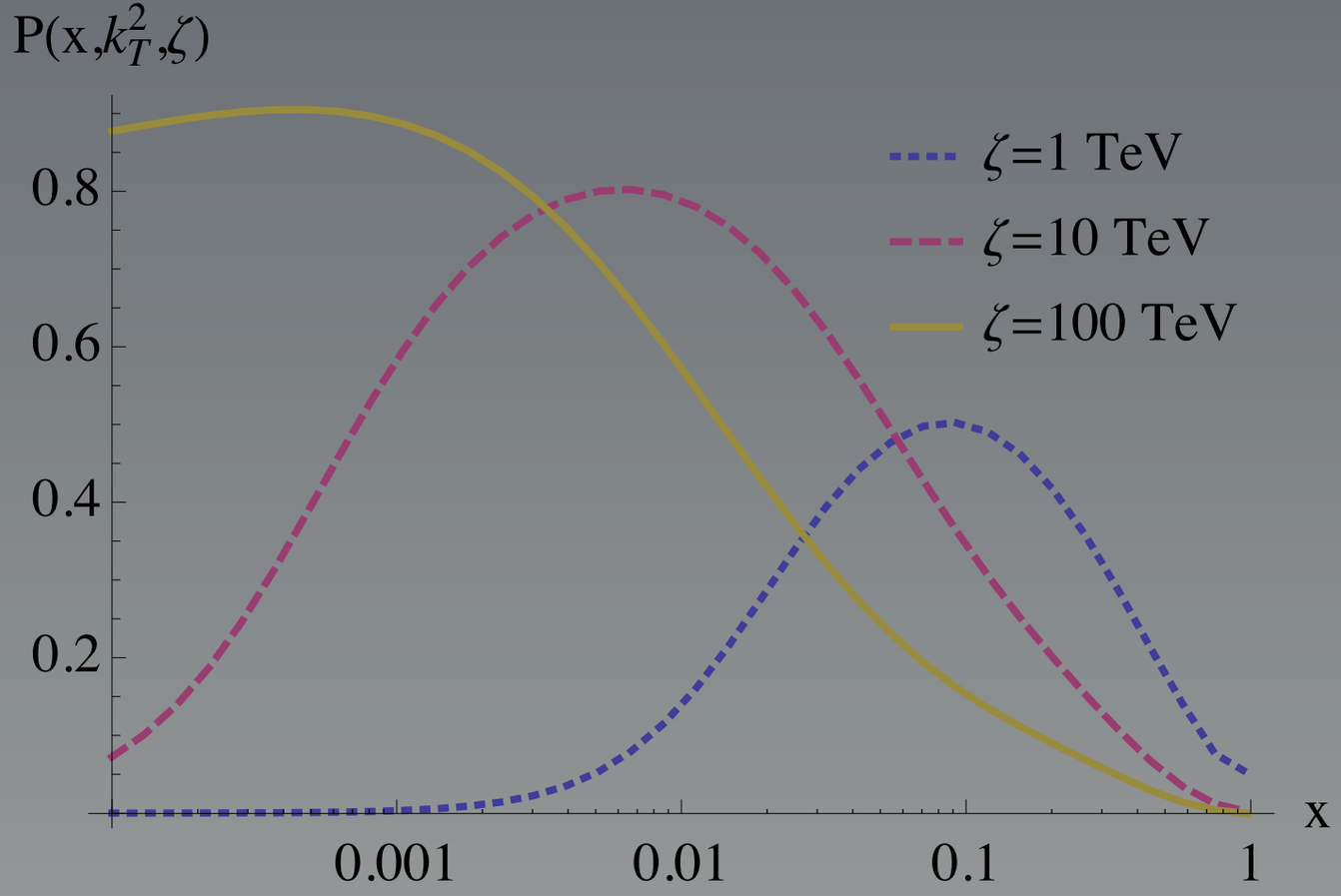
$$f_{1\mathrm{tail}}^{g}(x,\mathbf{k}_T^2,\zeta,\mu) = -\frac{\alpha_s}{\pi^2 k_T^2}\int_x^1 \frac{dz}{z}\Bigg[C_A\Bigg\{\frac{1-z}{z}+z(1-z)+\frac{z}{(1-z)^+}-\frac{1}{2}\delta(z-1)\times \left(1+\log\left[\frac{-k_T^2}{x^2(1-x)^2\zeta^2}\right]\right)\Bigg\}f_1^g\left(\frac{x}{z},\mu_0\right)+C_F\frac{1+(1-z)^2}{2z}\sum_{q,\bar{q}} f_1^q\left(\frac{x}{z},\mu_0\right)\Bigg]$$

cf. Ji, Ma, Yuan
JHEP07 (2005) 020

$$h_{1\mathrm{tail}}^{\perp g}(x,\mathbf{k}_T^2,\zeta,\mu) = \frac{\alpha_s}{\pi^2 k_T^2}\frac{2M_p^2}{k_T^2}\int_x^1 \frac{dz}{z}\frac{1-z}{z}\left[C_A f_1^g\left(\frac{x}{z},\mu_0\right)+C_F\sum_{q,\bar{q}} f_1^q\left(\frac{x}{z},\mu_0\right)\right]$$

cf. Sun, Xiao, Yuan
PR D84, 094005 (2011)

# DEGREE OF POLARIZATION

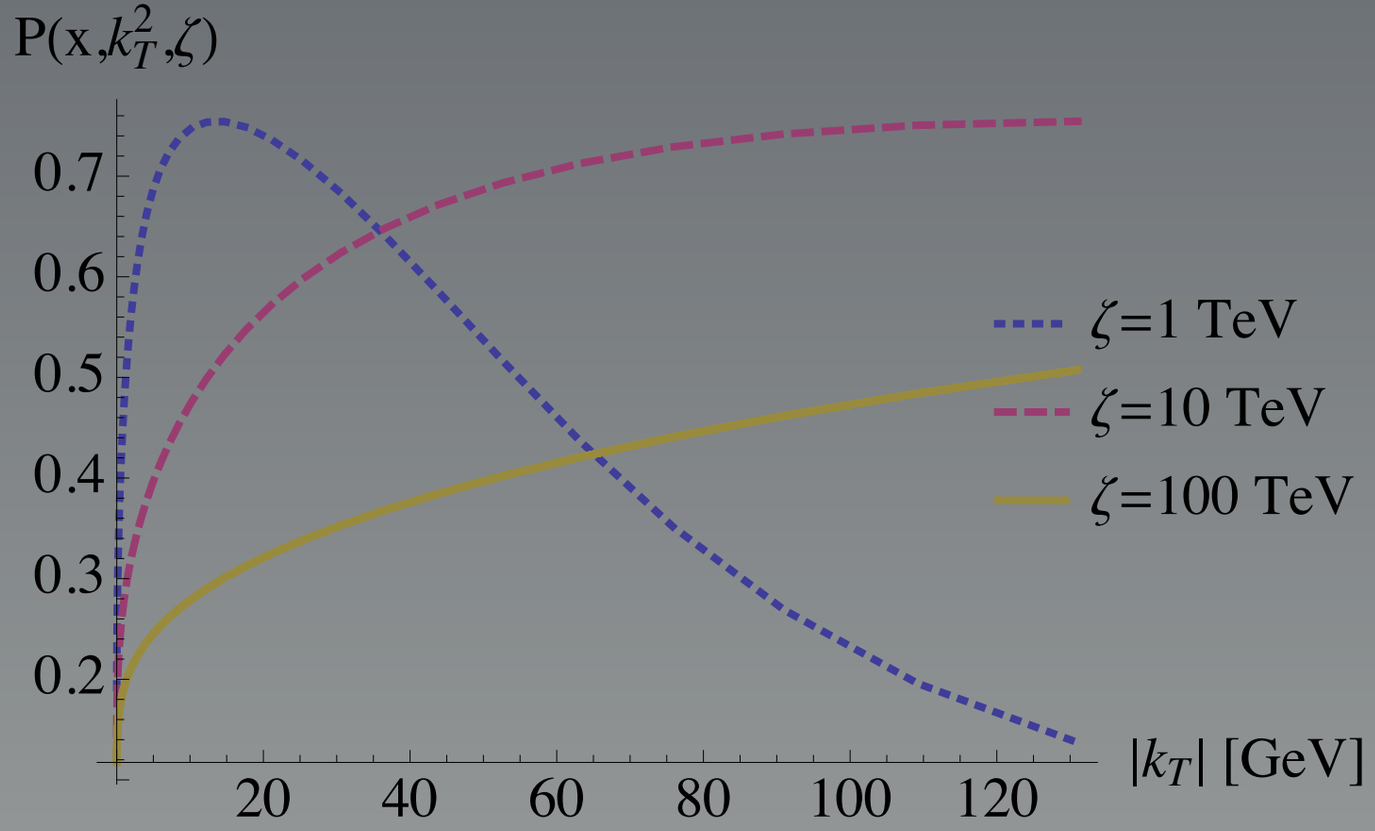



$$\mathcal{P}(x, \boldsymbol{p}_T, \zeta) \equiv \frac{h_1^{\perp g}(x, \boldsymbol{p}_T, \zeta, \mu)}{\frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T, \zeta, \mu)}$$

at fixed $k_T = 100\,\mathrm{GeV}$

CGC model predicts full polarization at small x and large kT:
A. Metz and J. Zhou, Phys. Rev. D 84, 051503 (2011)

# DEGREE OF POLARIZATION




$$\mathcal{P}(x, \boldsymbol{p}_T, \zeta) \equiv \frac{h_1^{\perp g}(x, \boldsymbol{p}_T, \zeta, \mu)}{\frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T, \zeta, \mu)}$$

at fixed $x = 125/8000$

CGC model predicts full polarization at small x and large kT:
A. Metz and J. Zhou, Phys. Rev. D 84, 051503 (2011)

# CALCULATION OF THE GLUON TMDS

- Possible for large pT
- Gluon polarization found to be large
  (up to 80% in kinematical region
  relevant for Higgs production)

for more info
arXiv:1310.4965

# OUTLINE

- Intro TMD factorization
- Calculation of TMDs
- **TMD effects in Higgs production**
- How to measure the gluon TMDs

HIGGS
spin?
spin-0
spin-1
spin-2

HIGGS

spin?

spin-0

spin-1

spin-2

partity?

$0^+$

$0^-$

$2^+_m\ 2^+_h\ 2^+_{h'}\ 2^+_{h''}$

$2^-_h$

HIGGS

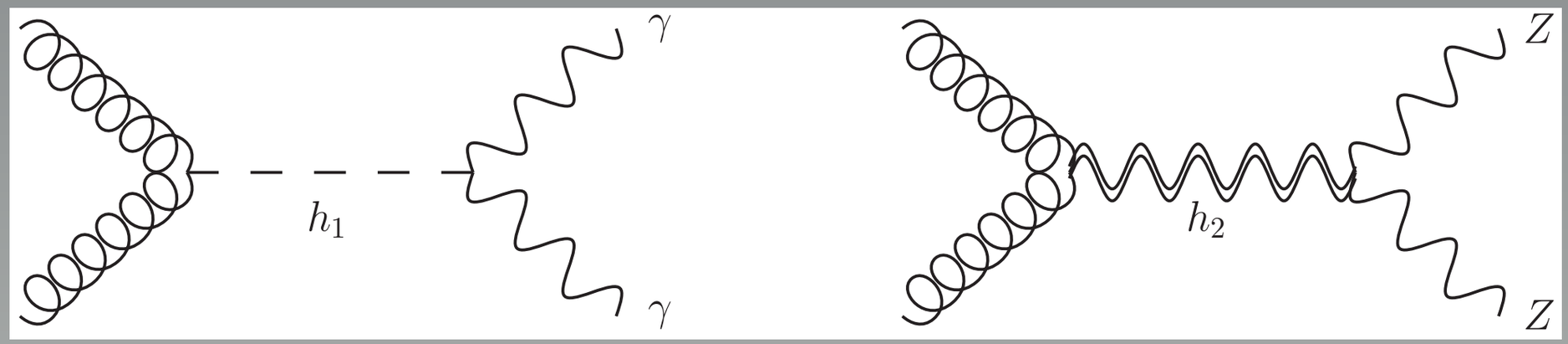
spin?

spin-0 | ~~spin-1~~ | spin-2

partity?

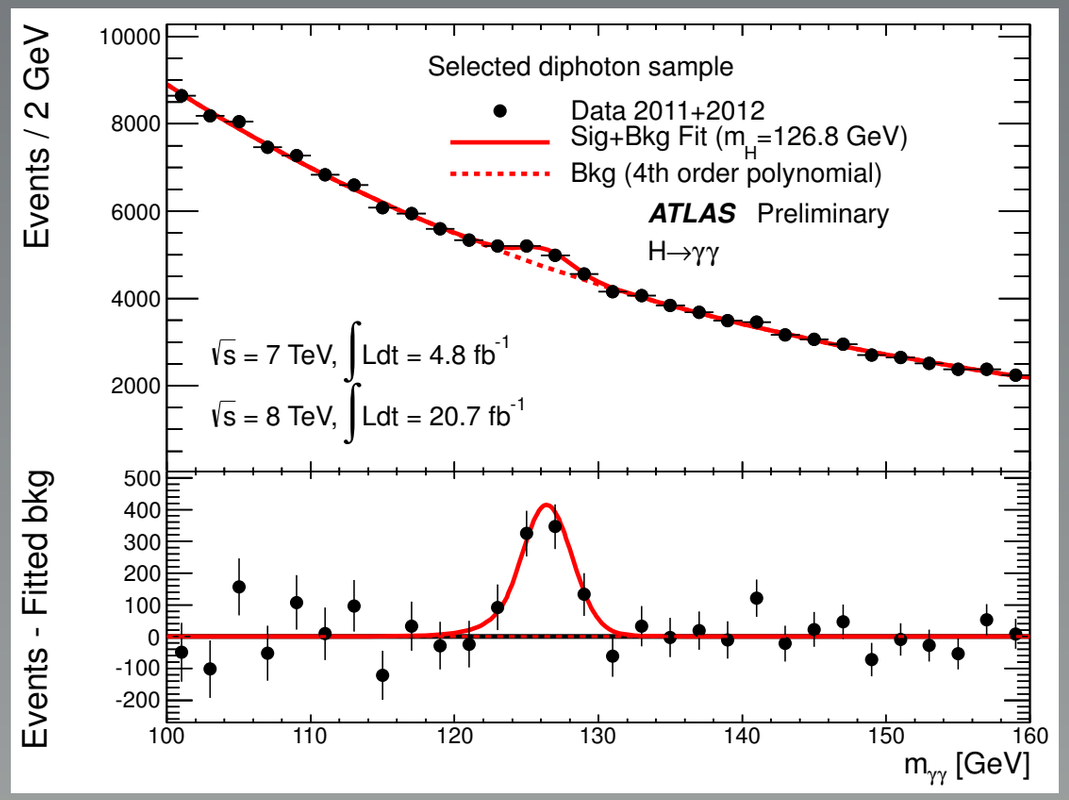
$0^+$ | $0^-$ | $2^+_m\ 2^+_h\ 2^+_{h'}\ 2^+_{h''}$ | $2^-_h$

different channels equal?



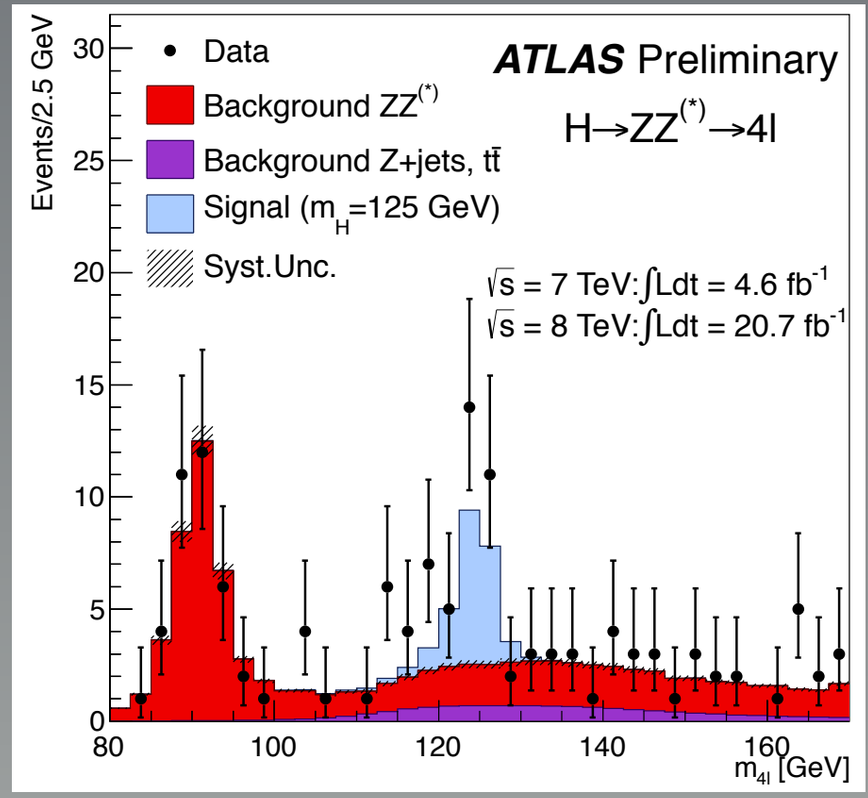
# Higgs $J^P$ Determination

## di-photon




ATLAS-CONF-2013-012

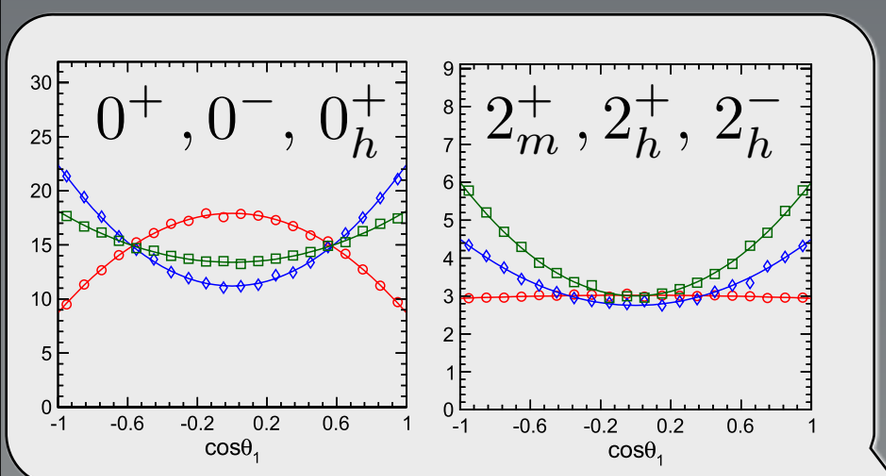
## $ZZ^* \rightarrow 4l$

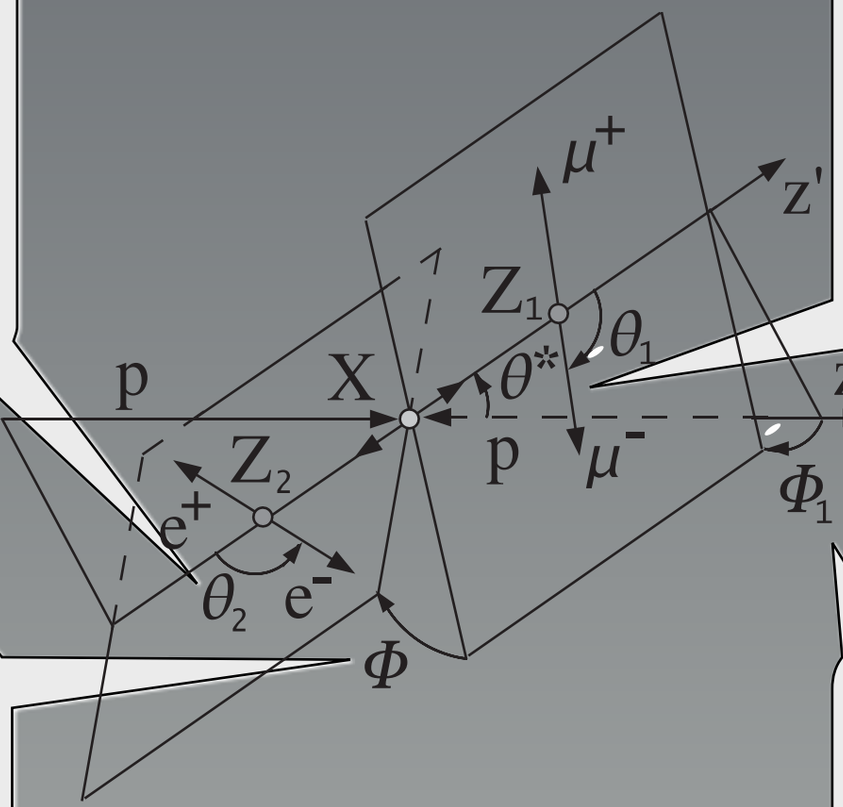


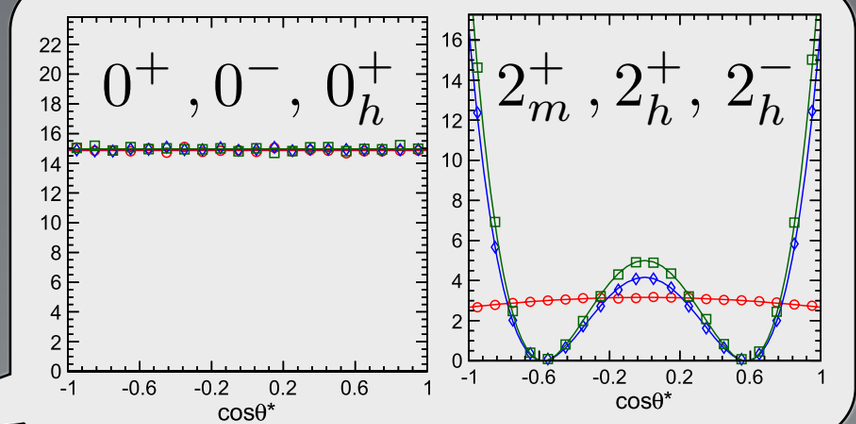

ATLAS-CONF-2013-013

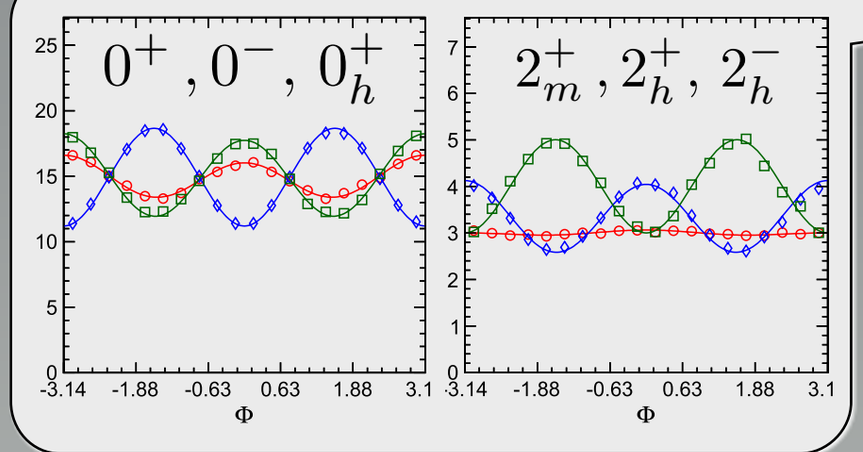
# Higgs $J^P$ Determination

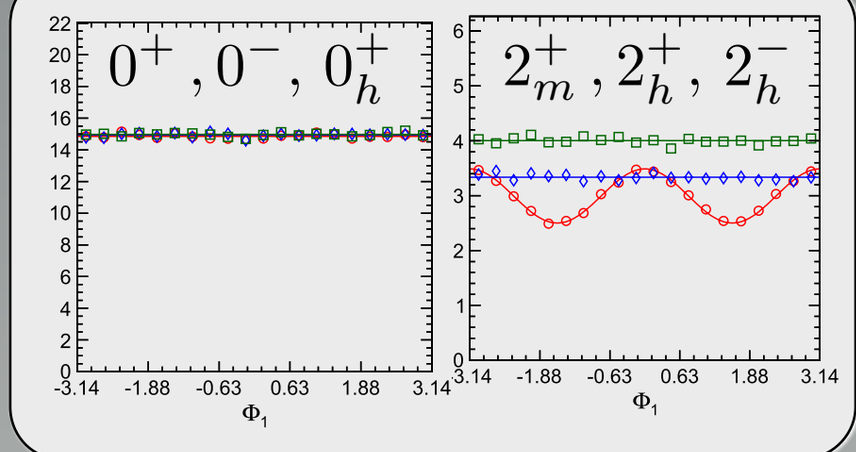
$ZZ^* \to 4l$



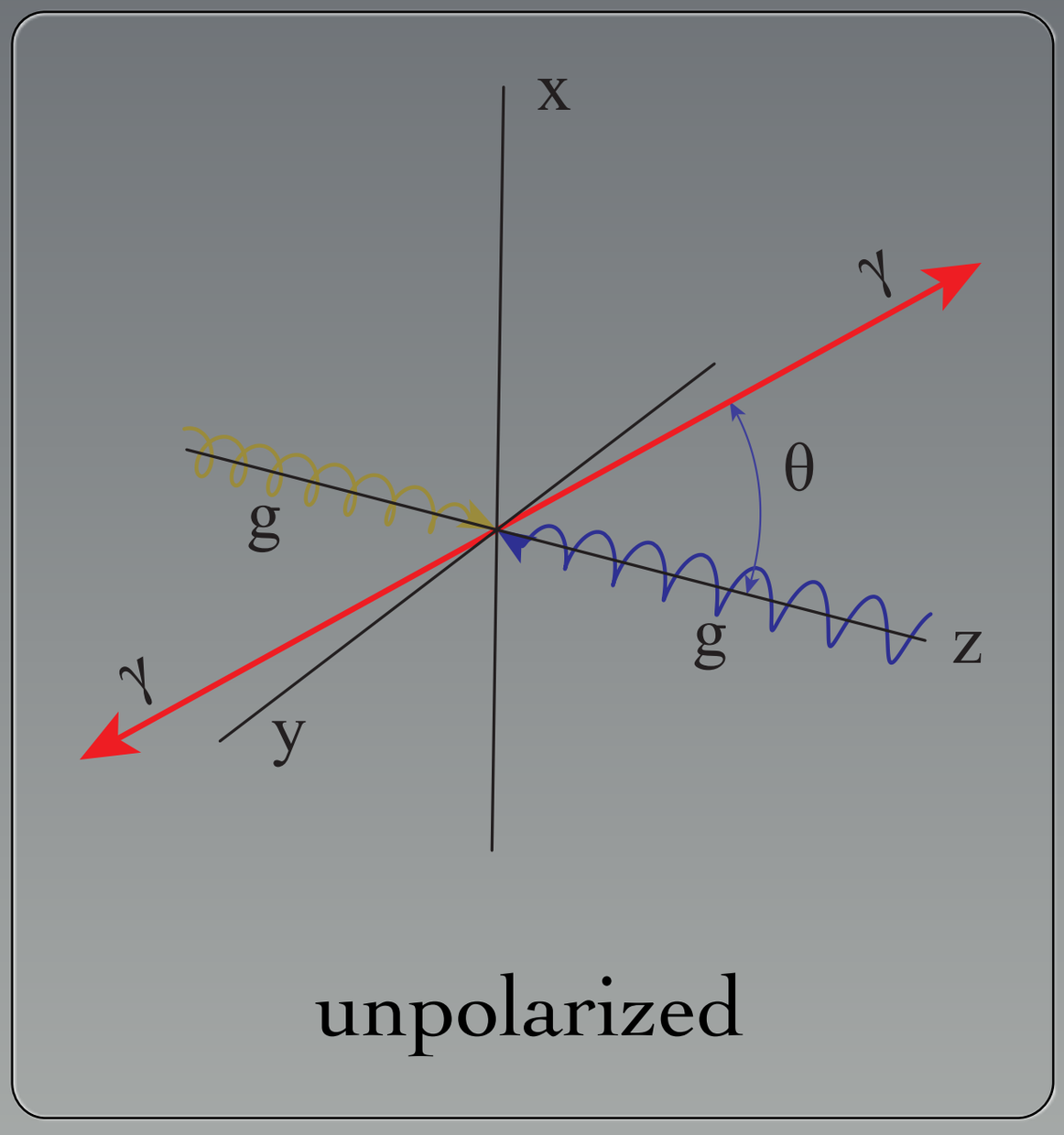




PR D81, 075022 (2010)

PR D86, 095031 (2012)

# Higgs $J^P$ Determination

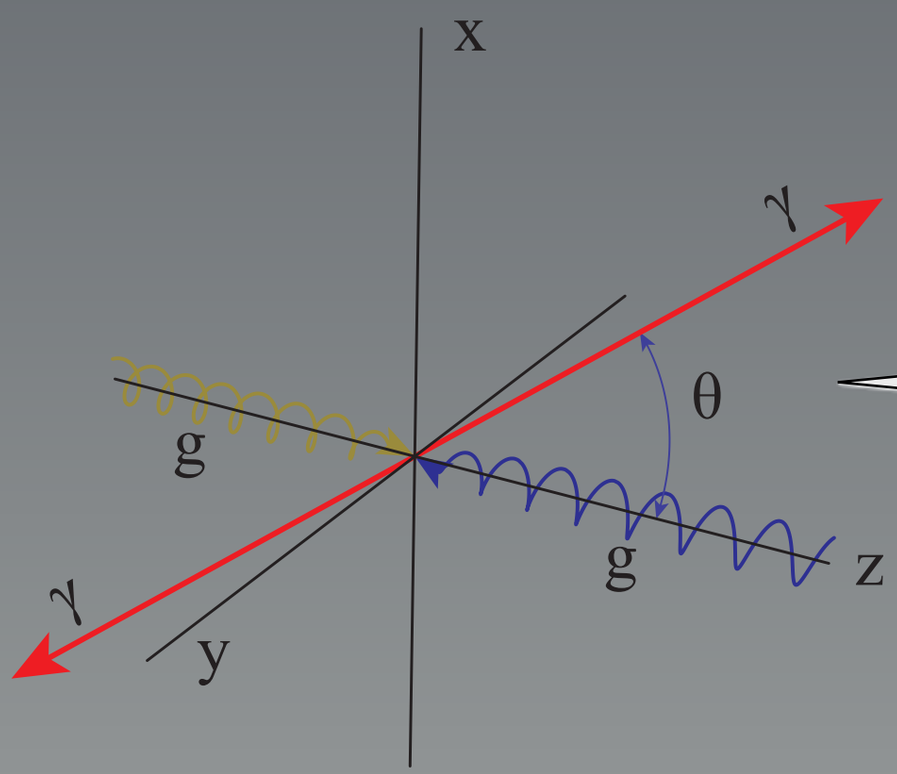
di-photon

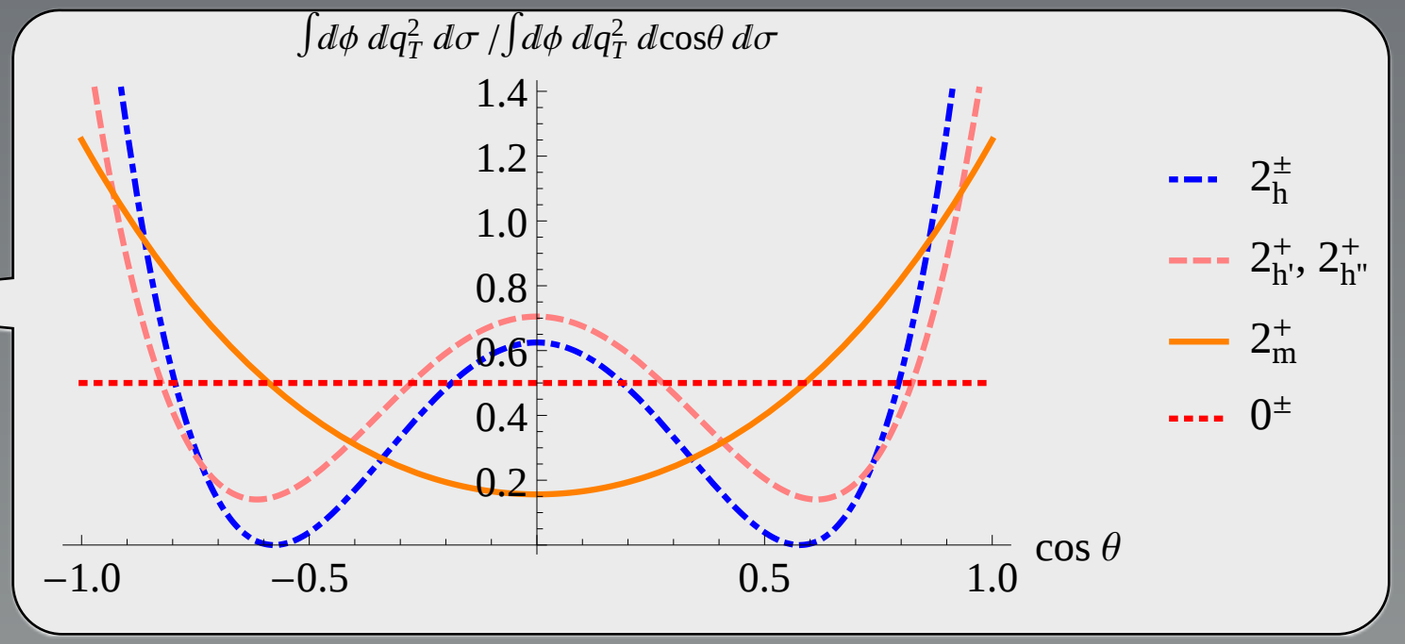



unpolarized

# Higgs $J^P$ Determination

di-photon

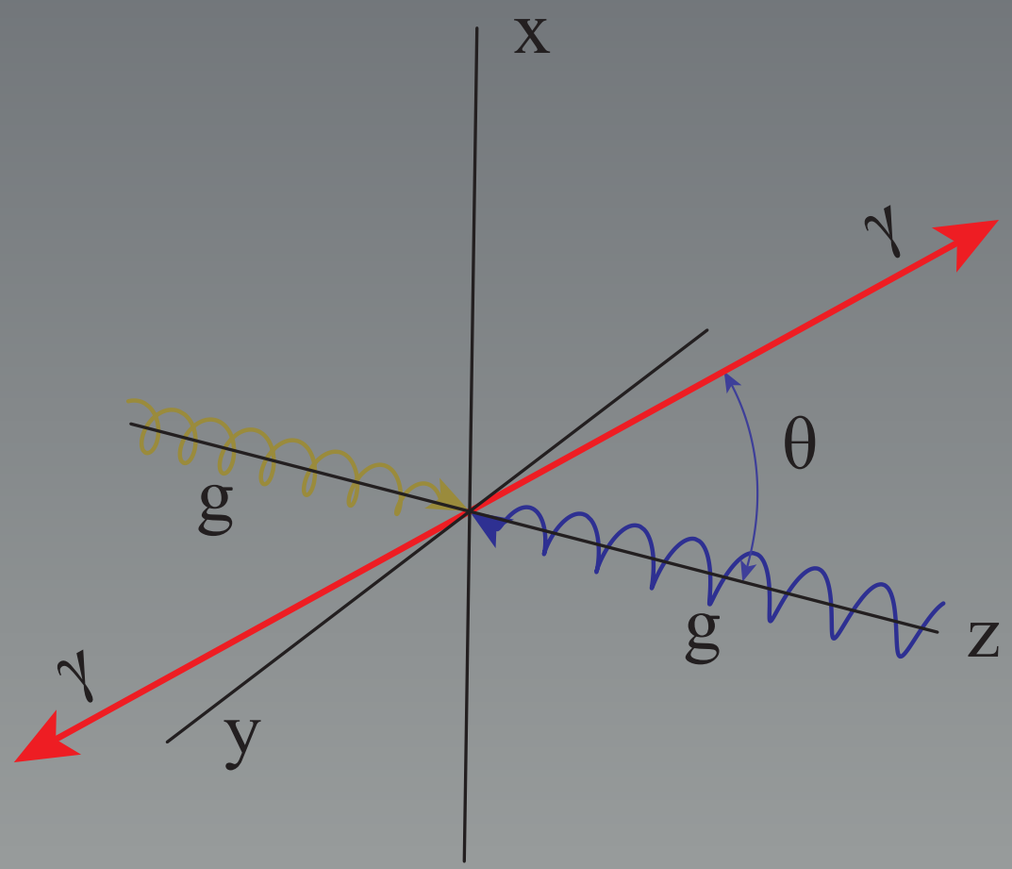


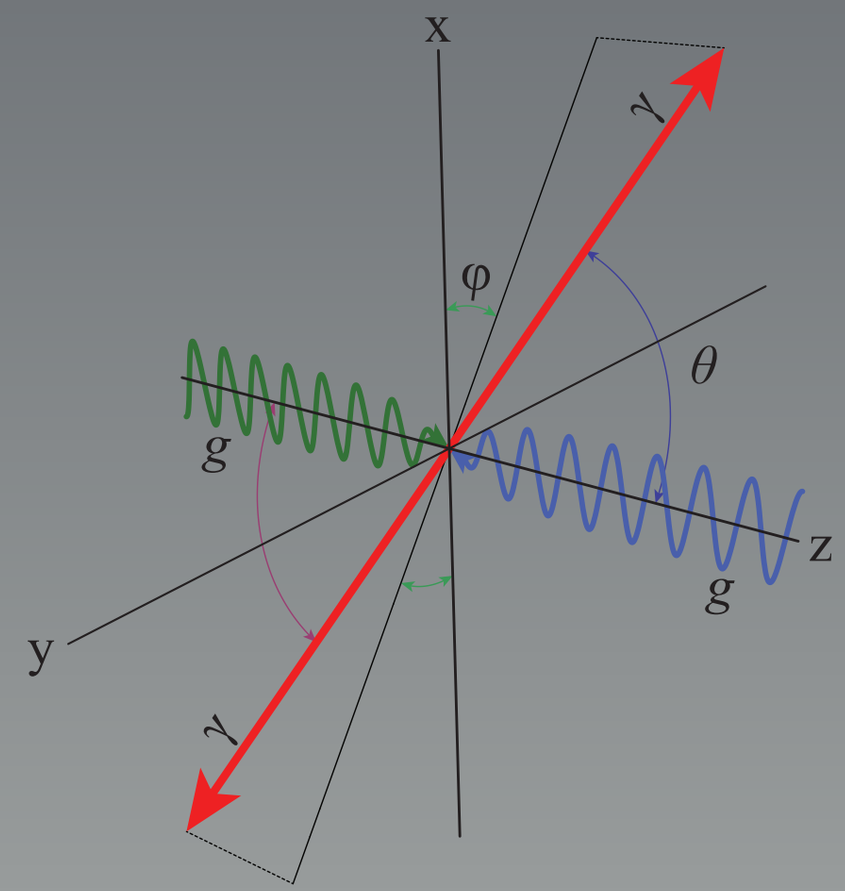

unpolarized

# Higgs $J^P$ Determination

## di-photon




unpolarized




polarized

# GENERAL STRUCTURE

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} \propto$$

$$F_1(Q,\theta)\,\mathcal{C}\,[f_1^g f_1^g] +$$

$$F_2(Q,\theta)\,\mathcal{C}\left[w_2\, h_1^{\perp g} h_1^{\perp g}\right] +$$

$$F_3(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} + h_1^{\perp g} f_1^g)\right]\cos(2\phi) +$$

$$F_3'(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} - h_1^{\perp g} f_1^g)\right]\sin(2\phi) +$$

$$F_4(Q,\theta)\,\mathcal{C}\left[w_4\, h_1^{\perp g} h_1^{\perp g}\right]\cos(4\phi) +$$

$$\mathcal{O}\,(q_T/Q)$$

φ azimuthal Collins-Soper angle

# GENERAL STRUCTURE

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} \propto$$

$$F_1(Q,\theta)\,\mathcal{C}\left[f_1^g f_1^g\right] +$$

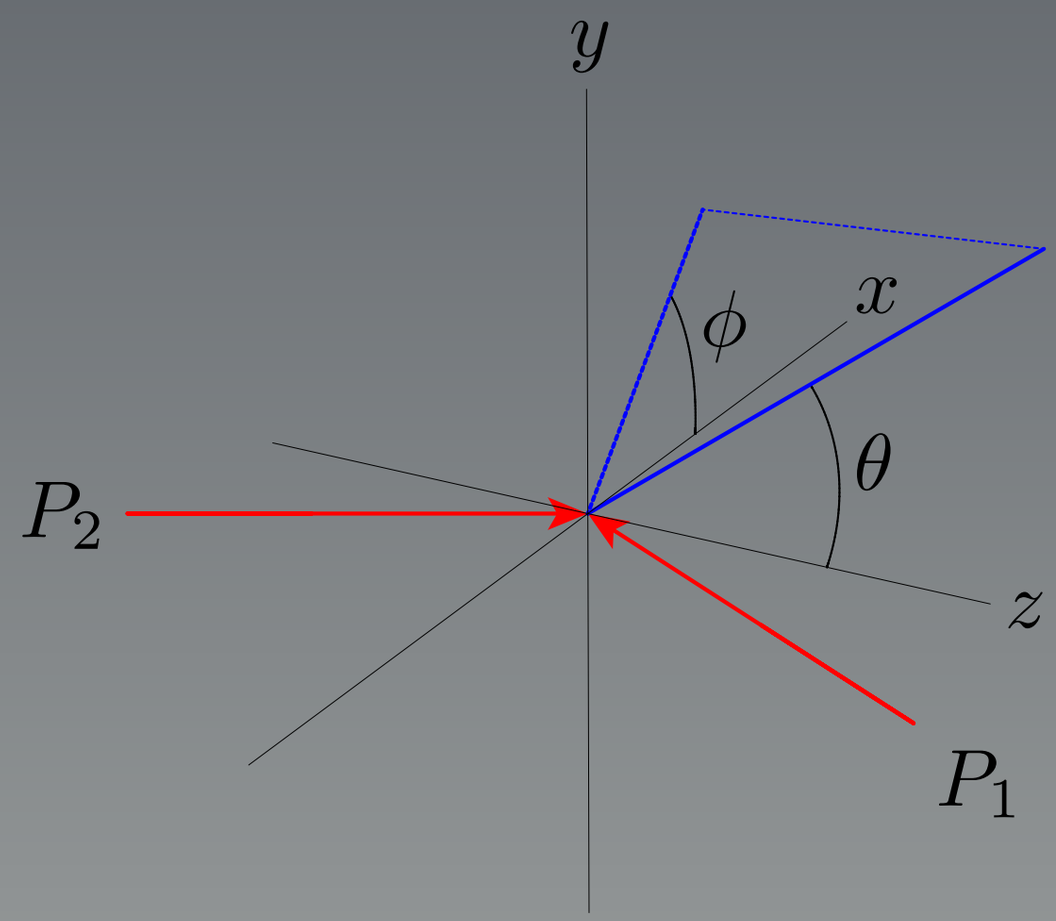
$$F_2(Q,\theta)\,\mathcal{C}\left[w_2\, h_1^{\perp g} h_1^{\perp g}\right] +$$

$$F_3(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} + h_1^{\perp g} f_1^g)\right]\cos(2\phi) +$$

$$F_3'(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} - h_1^{\perp g} f_1^g)\right]\sin(2\phi) +$$

$$F_4(Q,\theta)\,\mathcal{C}\left[w_4\, h_1^{\perp g} h_1^{\perp g}\right]\cos(4\phi) +$$

$$\mathcal{O}\left(q_T/Q\right)$$




φ azimuthal Collins-Soper angle

Collins-Soper frame

# GENERAL STRUCTURE

$$F_1 = \sum_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} M^{\lambda_1\lambda_2\lambda_3\lambda_4} \left(M^{\lambda_1\lambda_2\lambda_3\lambda_4}\right)^*$$

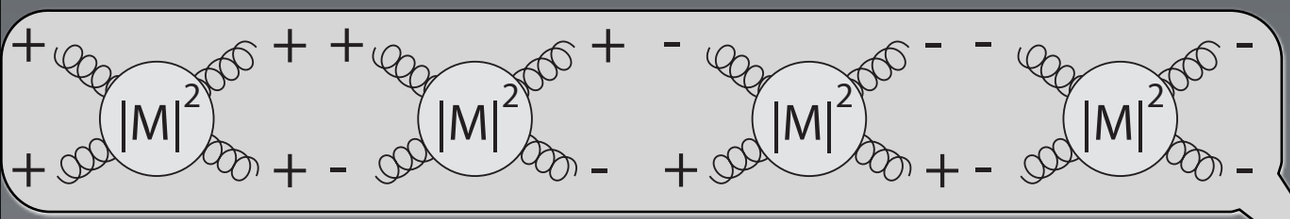
$$F_2 = 2\sum_{\lambda_3,\lambda_4} \mathrm{Re}\left[M^{++\lambda_3\lambda_4} \left(M^{--\lambda_3\lambda_4}\right)^*\right]$$

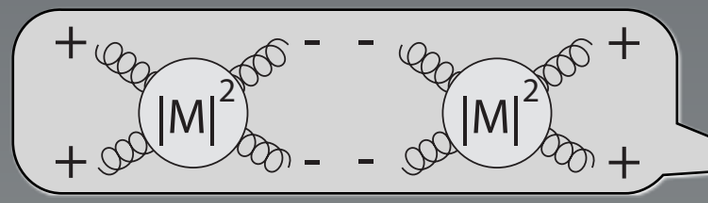
$$F_3 = \sum_{\lambda,\lambda_3,\lambda_4} \mathrm{Re}\left[M^{\lambda-\lambda_3\lambda_4} \left(M^{\lambda+\lambda_3\lambda_4}\right)^* + M^{+\lambda\lambda_3\lambda_4} \left(M^{-\lambda\lambda_3\lambda_4}\right)^*\right]$$

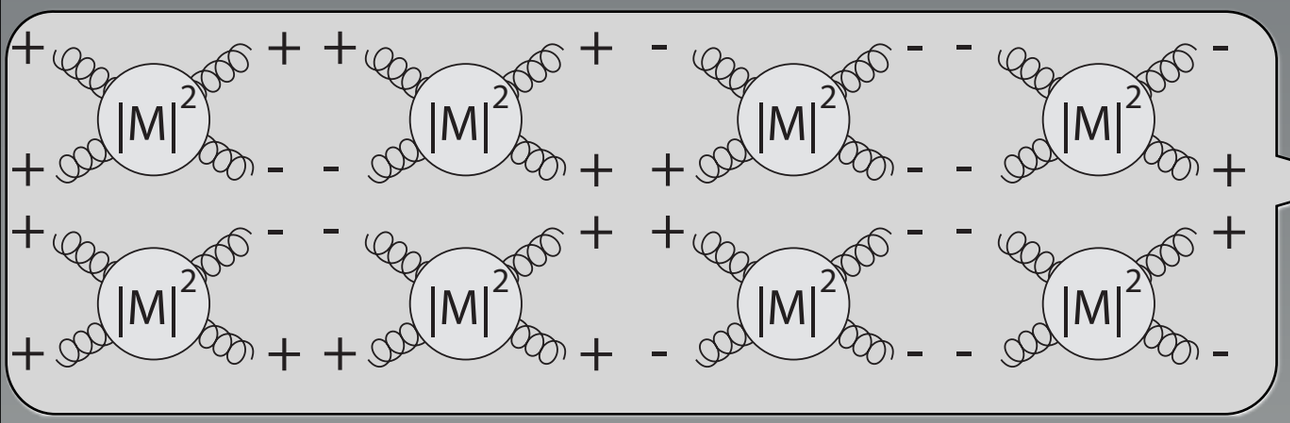
$$F_3' = \sum_{\lambda,\lambda_3,\lambda_4} \mathrm{Im}\left[M^{\lambda-\lambda_3\lambda_4} \left(M^{\lambda+\lambda_3\lambda_4}\right)^* - M^{+\lambda\lambda_3\lambda_4} \left(M^{-\lambda\lambda_3\lambda_4}\right)^*\right]$$

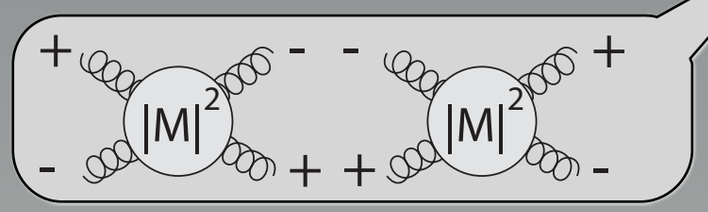
$$F_4 = 2\sum_{\lambda_3,\lambda_4} \mathrm{Re}\left[M^{+-\lambda_3\lambda_4} \left(M^{-+\lambda_3\lambda_4}\right)^*\right]$$

# GENERAL STRUCTURE




$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} \propto$$

$$F_1(Q,\theta)\,\mathcal{C}\left[f_1^g\,f_1^g\right] +$$

$$F_2(Q,\theta)\,\mathcal{C}\left[w_2\,h_1^{\perp g}h_1^{\perp g}\right] +$$

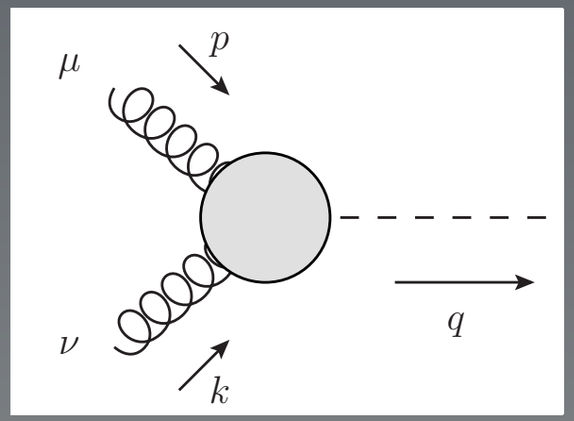
$$F_3(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} + h_1^{\perp g} f_1^g)\right]\cos(2\phi) +$$

$$F_3'(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} - h_1^{\perp g} f_1^g)\right]\sin(2\phi) +$$

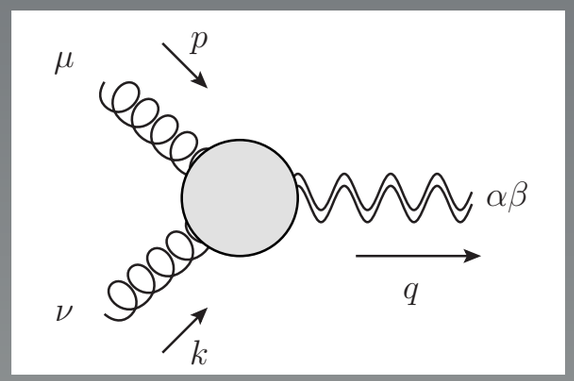
$$F_4(Q,\theta)\,\mathcal{C}\left[w_4\,h_1^{\perp g}h_1^{\perp g}\right]\cos(4\phi) +$$

$$\mathcal{O}\left(q_T/Q\right)$$

# PARTONIC AMPLITUDES



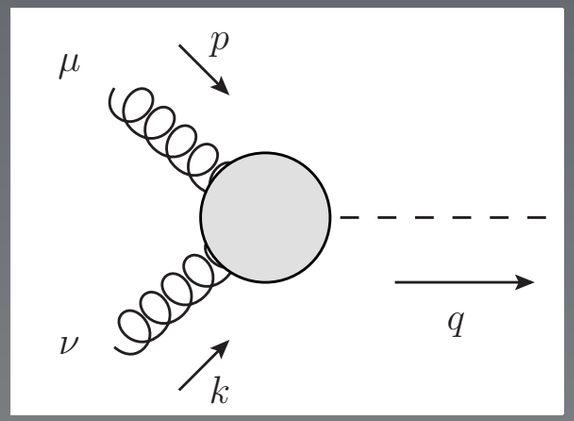

$$= a_1\, q^2 g^{\mu\nu} + a_3\, \epsilon^{pk\mu\nu}$$



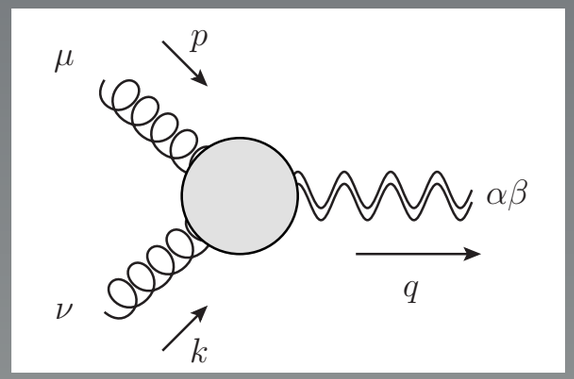

$$= \frac{1}{2} c_1\, q^2 g^{\mu\alpha} g^{\nu\beta} + \left[ c_2\, q^2 g^{\mu\nu} + c_5\, \epsilon^{pk\mu\nu} \right] \frac{(p-k)^\alpha (p-k)^\beta}{q^2}$$

Y. Gao et al., Phys. Rev. D 81, 075022 (2010)
S. Bolognesi et al., Phys. Rev. D 86, 095031 (2012)

# PARTONIC AMPLITUDES




$$= a_1\, q^2 g^{\mu\nu} + a_3\, \epsilon^{pk\mu\nu}$$




$$= \frac{1}{2} c_1\, q^2 g^{\mu\alpha} g^{\nu\beta} + \left[ c_2\, q^2 g^{\mu\nu} + c_5\, \epsilon^{pk\mu\nu} \right] \frac{(p-k)^\alpha (p-k)^\beta}{q^2}$$

| scenario | $0^+$ | $0^-$ | $2^+_m$ | $2^+_h$ | $2^+_{h'}$ | $2^+_{h''}$ | $2^-_h$ |
|---|---|---|---|---|---|---|---|
| $a_1$ | 1 | 0 | - | - | - | - | - |
| $a_3$ | 0 | 1 | - | - | - | - | - |
| $c_1$ | - | - | 1 | 0 | 1 | 1 | 0 |
| $c_2$ | - | - | $-\frac{1}{4}$ | 1 | 1 | $-\frac{3}{2}$ | 0 |
| $c_5$ | - | - | 0 | 0 | 0 | 0 | 1 |

Y. Gao et al., Phys. Rev. D 81, 075022 (2010)
S. Bolognesi et al., Phys. Rev. D 86, 095031 (2012)

# PARTONIC AMPLITUDES SPIN-0

$$M_{X_i} = \begin{pmatrix} M^{+-+-} & M^{+-++} & M^{+---} & M^{+--+} \\ M^{+++-} & M^{++++} & M^{++--} & M^{++-+} \\ M^{--+-} & M^{--++} & M^{----} & M^{---+} \\ M^{-++-} & M^{-+++} & M^{-+--} & M^{-+-+} \end{pmatrix}$$

$$M_{X_0} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & V_{gg0}^{++} V_{\gamma\gamma 0}^{++\,*} & V_{gg0}^{++} V_{\gamma\gamma 0}^{--\,*} & 0 \\ 0 & V_{gg0}^{--} V_{\gamma\gamma 0}^{++\,*} & V_{gg0}^{--} V_{\gamma\gamma 0}^{--\,*} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$V_{gg0}^{++} = V_{\gamma\gamma 0}^{++} = a_1 + \frac{1}{2} i a_3$$

$$V_{gg0}^{--} = V_{\gamma\gamma 0}^{--} = a_1 - \frac{1}{2} i a_3$$

# PARTONIC AMPLITUDES SPIN-1

$$M_{X_i} = \begin{pmatrix} M^{+-+-} & M^{+-++} & M^{+---} & M^{+--+} \\ M^{+++-} & M^{++++} & M^{++--} & M^{++-+} \\ M^{--+-} & M^{--++} & M^{----} & M^{---+} \\ M^{-++-} & M^{-+++} & M^{-+--} & M^{-+-+} \end{pmatrix}$$

$$M_{X_1} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -V_{gg1}^{++} V_{\gamma\gamma 1}^{++\,*} \cos\theta & -V_{gg1}^{++} V_{\gamma\gamma 1}^{--\,*} \cos\theta & 0 \\ 0 & -V_{gg1}^{--} V_{\gamma\gamma 1}^{++\,*} \cos\theta & -V_{gg1}^{--} V_{\gamma\gamma 1}^{--\,*} \cos\theta & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

# PARTONIC AMPLITUDES SPIN-2

$$M_{X_i} = \begin{pmatrix} M^{+-+-} & M^{+-++} & M^{+---} & M^{+--+} \\ M^{+++-} & M^{++++} & M^{++--} & M^{++-+} \\ M^{--+-} & M^{--++} & M^{----} & M^{---+} \\ M^{-++-} & M^{-+++} & M^{-+--} & M^{-+-+} \end{pmatrix}$$

$$M_{X_2} = \begin{pmatrix} V_{gg2}^{+-} V_{\gamma\gamma 2}^{+-\,*} \cos^4\left(\frac{\theta}{2}\right) & V_{gg2}^{+-} V_{\gamma\gamma 2}^{++\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) & V_{gg2}^{+-} V_{\gamma\gamma 2}^{--\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) & V_{gg2}^{+-} V_{\gamma\gamma 2}^{-+\,*} \sin^4\left(\frac{\theta}{2}\right) \\ V_{gg2}^{++} V_{\gamma\gamma 2}^{+-\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) & V_{gg2}^{++} V_{\gamma\gamma 2}^{++\,*} \frac{3\cos(2\theta)+1}{4} & V_{gg2}^{++} V_{\gamma\gamma 2}^{--\,*} \frac{3\cos(2\theta)+1}{4} & V_{gg2}^{++} V_{\gamma\gamma 2}^{-+\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) \\ V_{gg2}^{--} V_{\gamma\gamma 2}^{+-\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) & V_{gg2}^{--} V_{\gamma\gamma 2}^{++\,*} \frac{3\cos(2\theta)+1}{4} & V_{gg2}^{--} V_{\gamma\gamma 2}^{--\,*} \frac{3\cos(2\theta)+1}{4} & V_{gg2}^{--} V_{\gamma\gamma 2}^{-+\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) \\ V_{gg2}^{-+} V_{\gamma\gamma 2}^{+-\,*} \sin^4\left(\frac{\theta}{2}\right) & V_{gg2}^{-+} V_{\gamma\gamma 2}^{++\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) & V_{gg2}^{-+} V_{\gamma\gamma 2}^{--\,*} \sqrt{\frac{3}{8}} \sin^2(\theta) & V_{gg2}^{-+} V_{\gamma\gamma 2}^{-+\,*} \cos^4\left(\frac{\theta}{2}\right) \end{pmatrix}$$

$$\begin{aligned} V_{gg2}^{+-} &= V_{gg2}^{-+} = V_{\gamma\gamma 2}^{+-} = V_{\gamma\gamma 2}^{-+} = c_1, \\ V_{gg2}^{++} &= V_{\gamma\gamma 2}^{++} = \frac{1}{\sqrt{6}}[c_1 + 4c_2 - i2(c_5 - 2c_6)], \\ V_{gg2}^{--} &= V_{\gamma\gamma 2}^{--} = \frac{1}{\sqrt{6}}[c_1 + 4c_2 + i2(c_5 - 2c_6)], \end{aligned}$$

# GENERAL STRUCTURE

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} \propto$$

$$F_1(Q,\theta)\,\mathcal{C}\,[f_1^g f_1^g] +$$

$$F_2(Q,\theta)\,\mathcal{C}\left[w_2\, h_1^{\perp g} h_1^{\perp g}\right] +$$

$$F_3(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} + h_1^{\perp g} f_1^g)\right]\cos(2\phi) +$$

$$F_3'(Q,\theta)\,\mathcal{C}\left[w_3(f_1^g h_1^{\perp g} - h_1^{\perp g} f_1^g)\right]\sin(2\phi) +$$

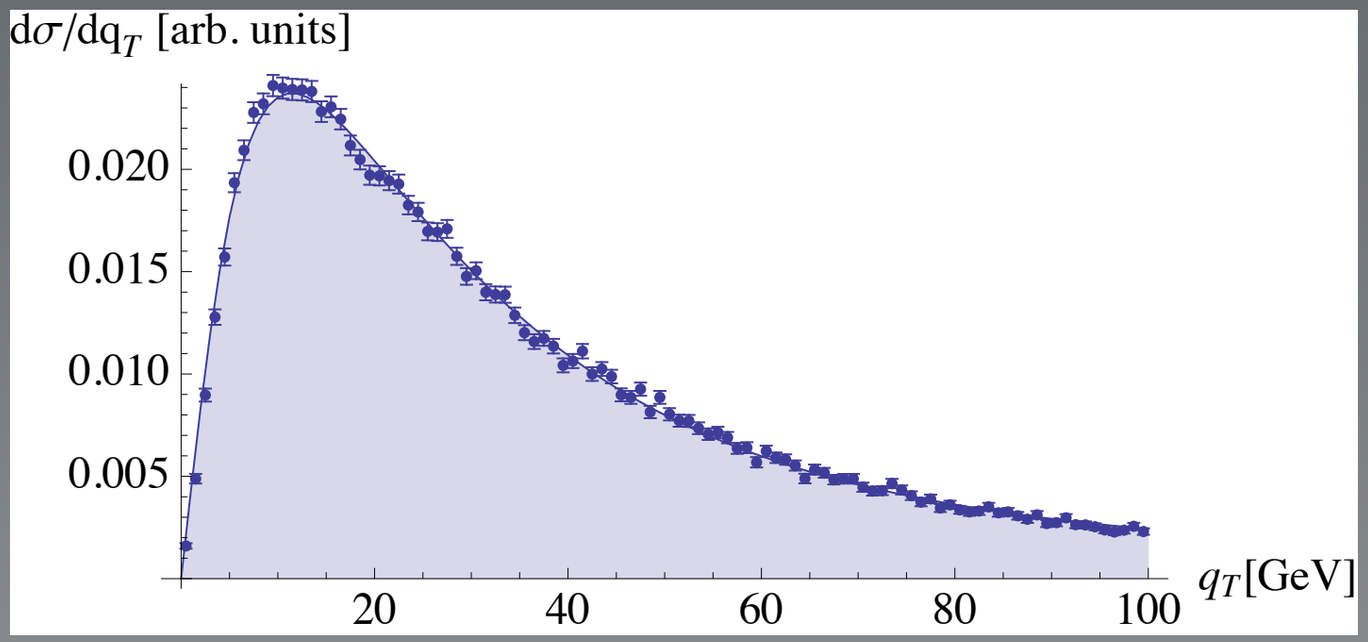
$$F_4(Q,\theta)\,\mathcal{C}\left[w_4\, h_1^{\perp g} h_1^{\perp g}\right]\cos(4\phi) +$$

$$\mathcal{O}\,(q_T/Q)$$

- Unpolarized distribution
- gluon TMD
- $f_1^g$

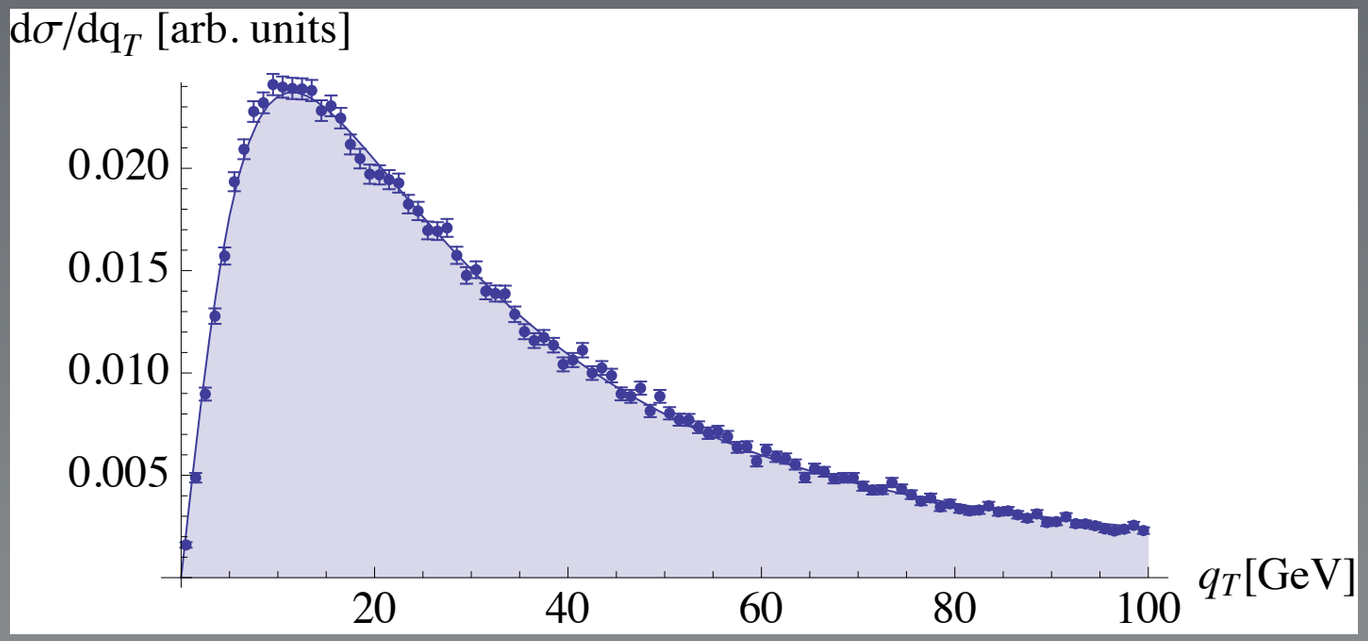
- Polarized distribution
- linearly polarized gluon distribution
- $h_1^{\perp g}$

# UNPOLARIZED DISTRIBUTION

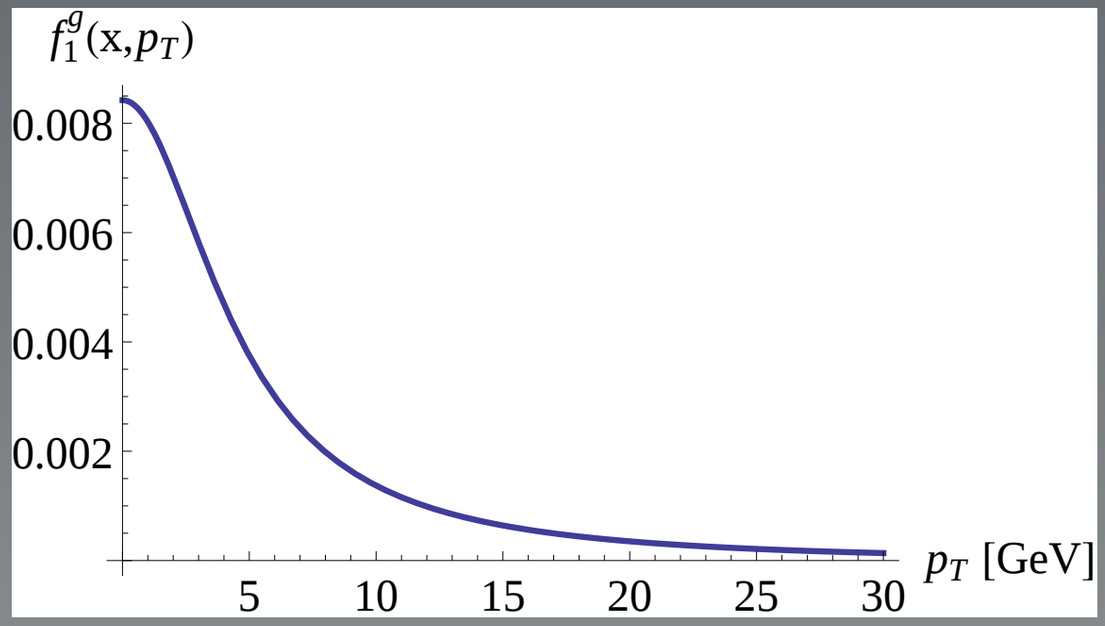



POWHEG+Pythia 8 Higgs qT distribution

# UNPOLARIZED DISTRIBUTION

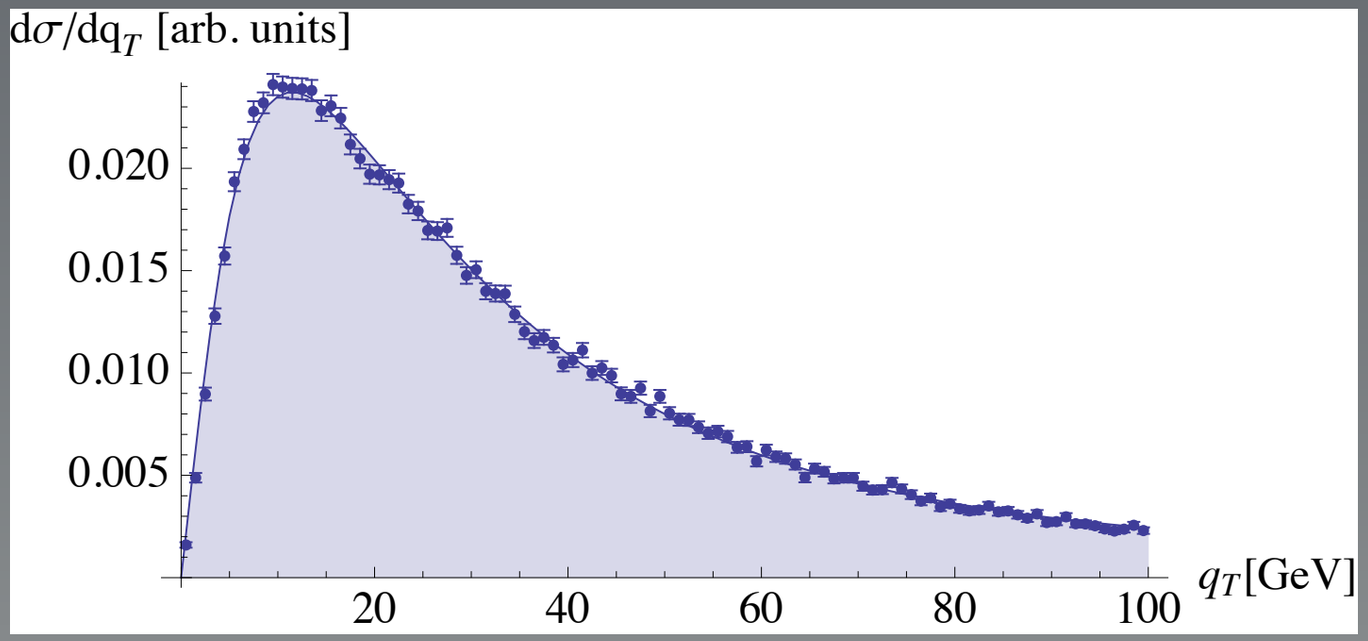



POWHEG+Pythia 8 Higgs qT distribution

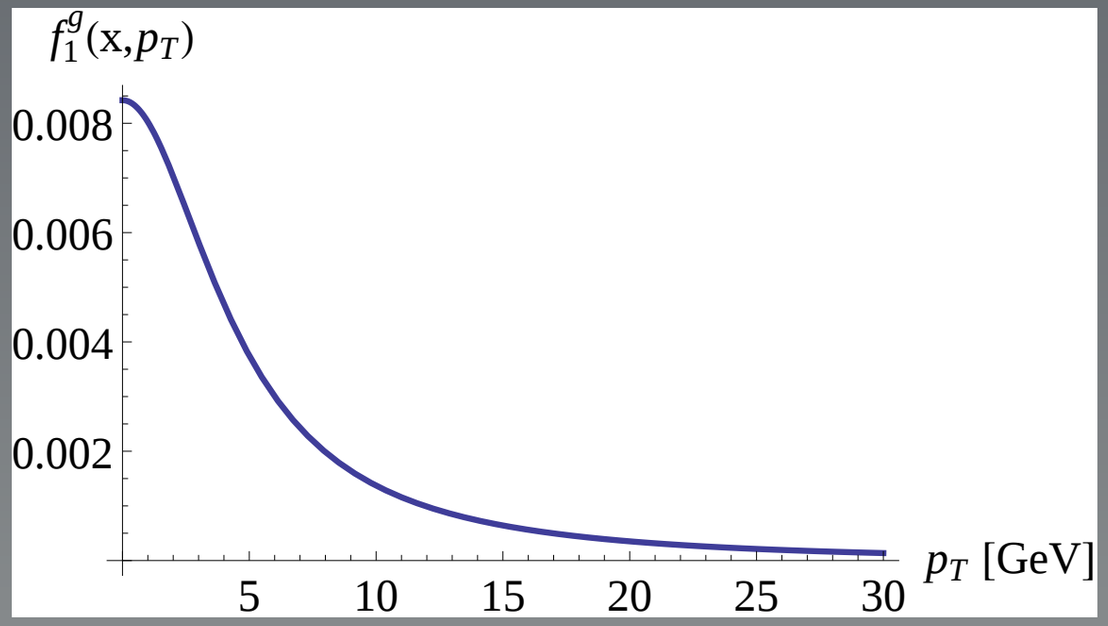



$$f_1^g(x, \boldsymbol{p}_T^2, \frac{3}{2}\sqrt{s}, M_h) = \frac{A_0\, M_0^2}{M_0^2 + \boldsymbol{p}_T^2} \exp\left[-\frac{\boldsymbol{p}_T^2}{a\boldsymbol{p}_T^2 + 2\sigma^2}\right]$$

# UNPOLARIZED DISTRIBUTION




POWHEG+Pythia 8 Higgs qT distribution




$$f_1^g(x, \boldsymbol{p}_T^2, \frac{3}{2}\sqrt{s}, M_h) = \frac{A_0\, M_0^2}{M_0^2 + \boldsymbol{p}_T^2} \exp\left[-\frac{\boldsymbol{p}_T^2}{a\boldsymbol{p}_T^2 + 2\sigma^2}\right]$$

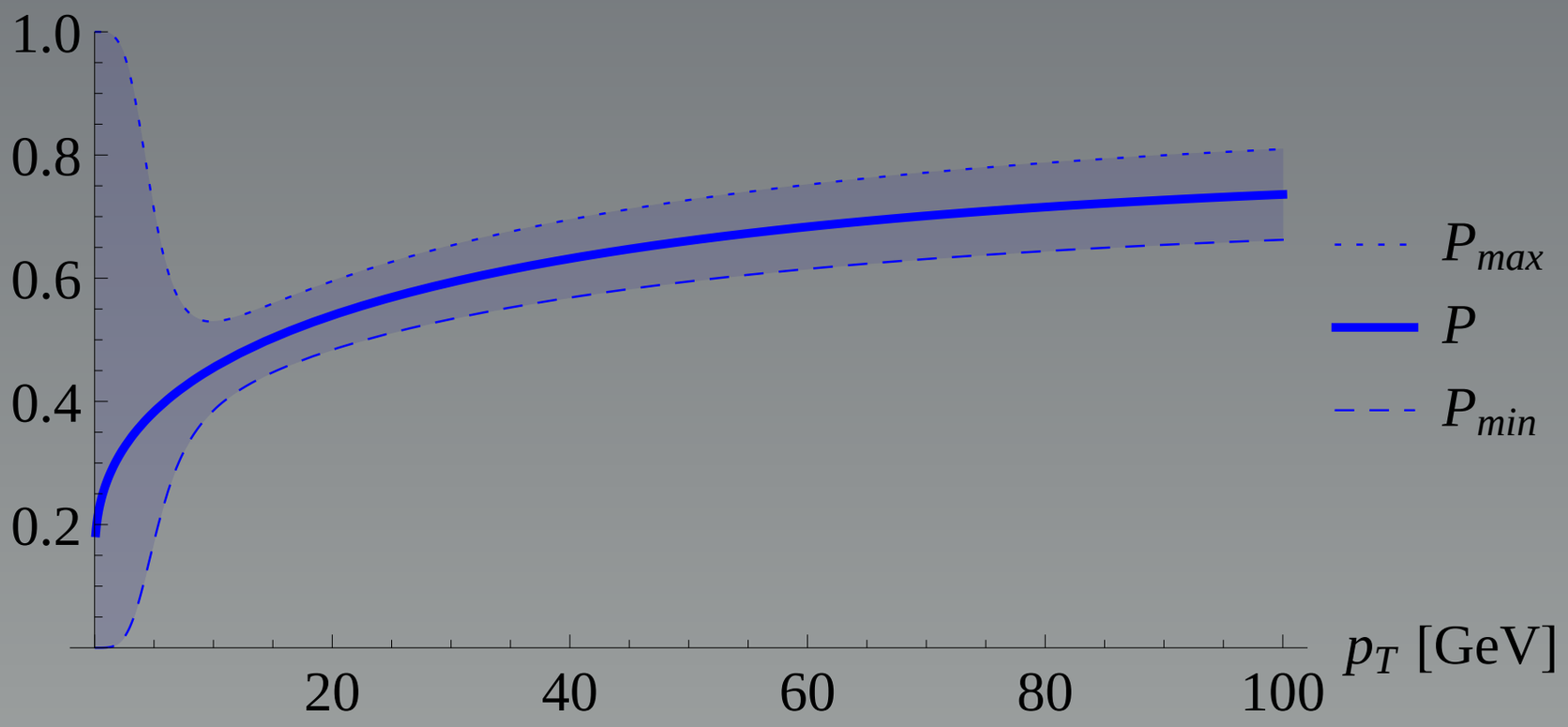
$$\sigma = 38.9 \text{ GeV}$$

$$a = 0.555$$

$$M_0 = 3.9 \text{ GeV}$$

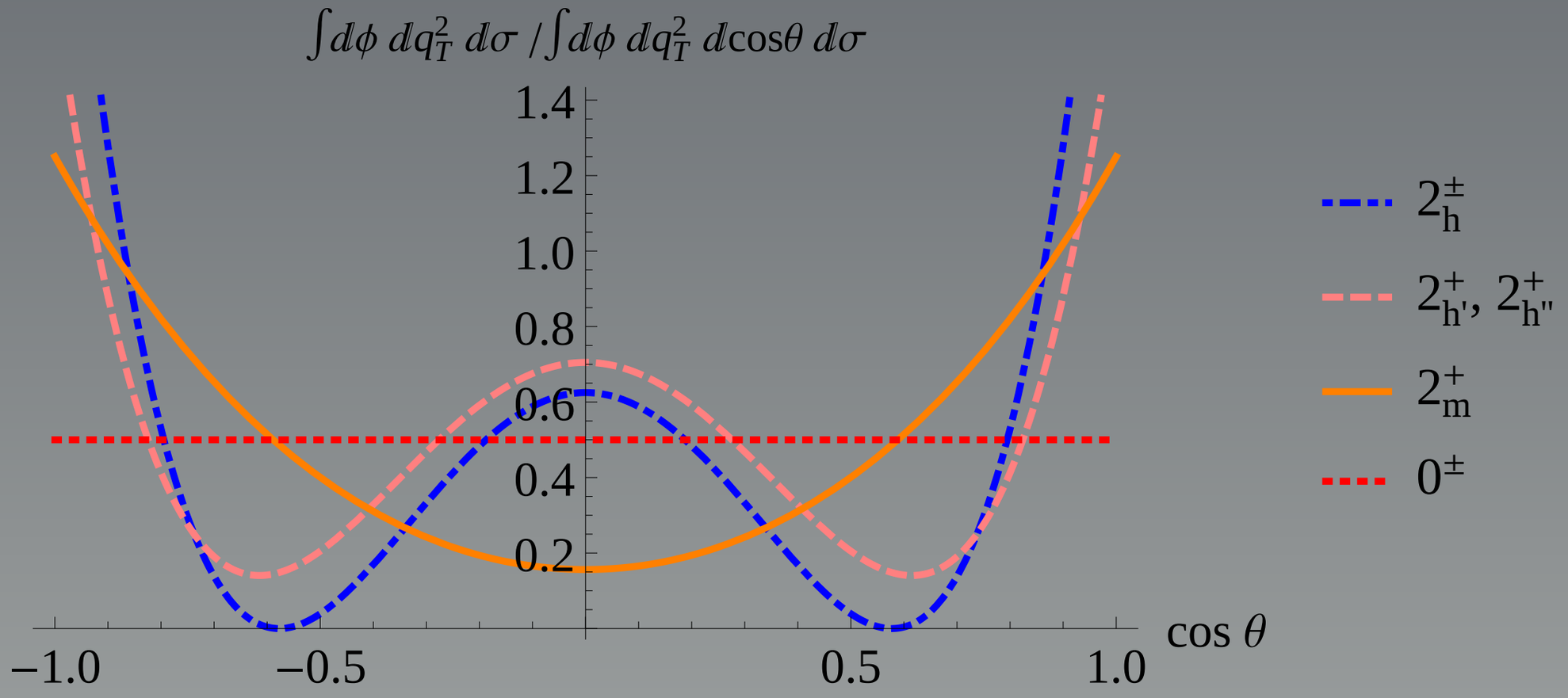
# POLARIZED DISTRIBUTION

$$\mathcal{P}(x, \boldsymbol{p}_T, \zeta) \equiv \frac{h_1^{\perp g}(x, \boldsymbol{p}_T, \zeta, \mu)}{\frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T, \zeta, \mu)}$$



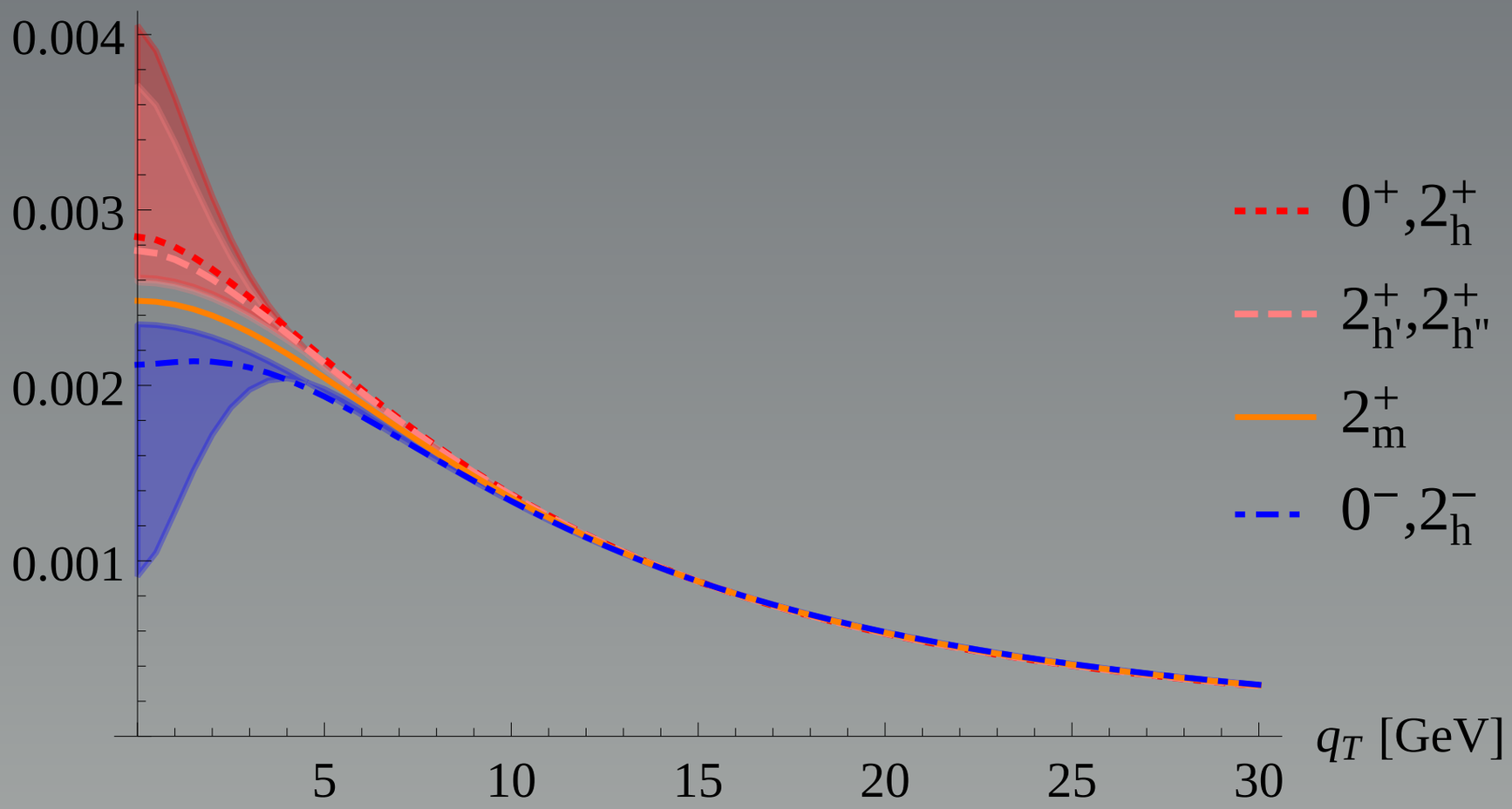

at fixed $x = \frac{m_H}{\sqrt{s}}$

# COSΘ DISTRIBUTION

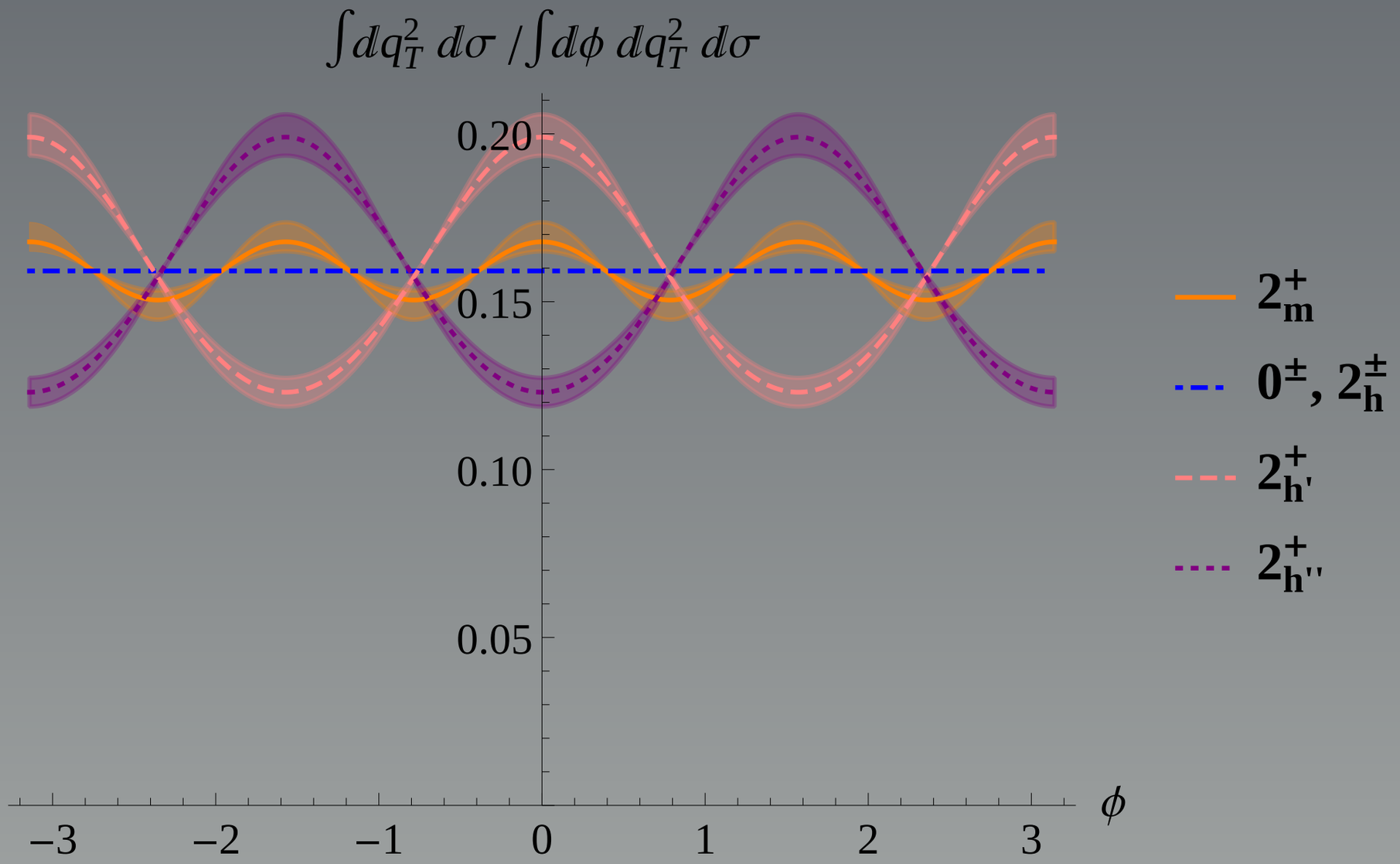


# TRANSVERSE MOMENTUM DISTRIBUTION

$$\int d\phi\, d\sigma \,/ \int d\phi\, dq_T^2\, d\sigma \;[\mathrm{GeV}^{-2}]$$



# Φ DISTRIBUTION



# REMARKS

- spin-2 with CP violating coupling ↔ sin2φ dependence
- gg → box → γγ background also φ dependent
- same can be done in the H→ZZ* channel

for gg → box → γγ see also
J.W. Qiu, M. Schlegel and W. Vogelsang,
Phys. Rev. Lett. 107, 062001 (2011)

# CONCLUSIONS

- gluon polarization modifies both Higgs $q_T$ and $\varphi$ distribution
- $q_T$ distribution different for positive/negative parity
- $\varphi$ distribution non-isotropic for various spin-2 scenarios
- this does not show up in event generators

for more info see
PRL 111, 032002 (2013)

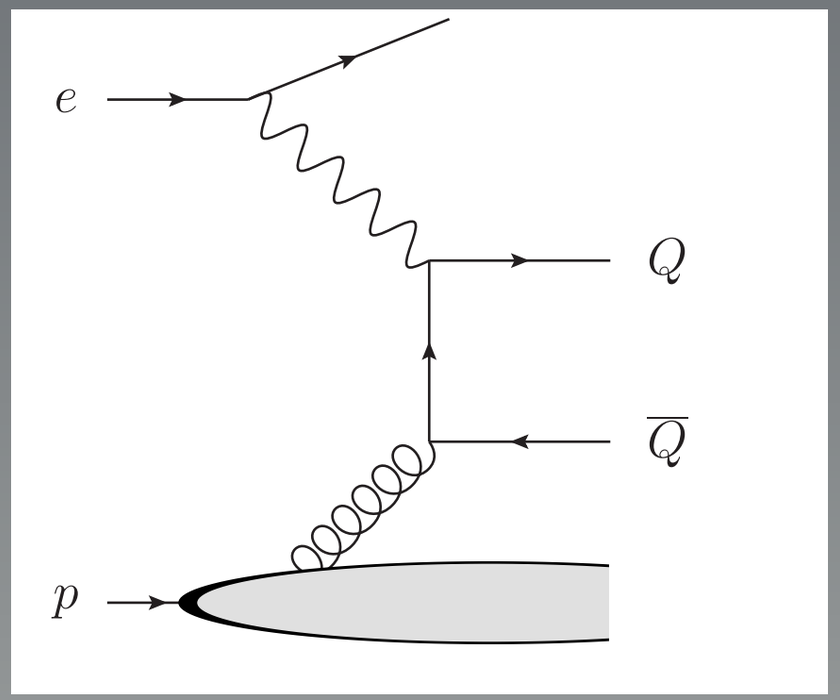
# OUTLINE

- Intro TMD factorization
- Calculation of TMDs
- TMD effects in Higgs production
- **How to measure the gluon TMDs**

# HOW TO MEASURE THE GLUON TMDS

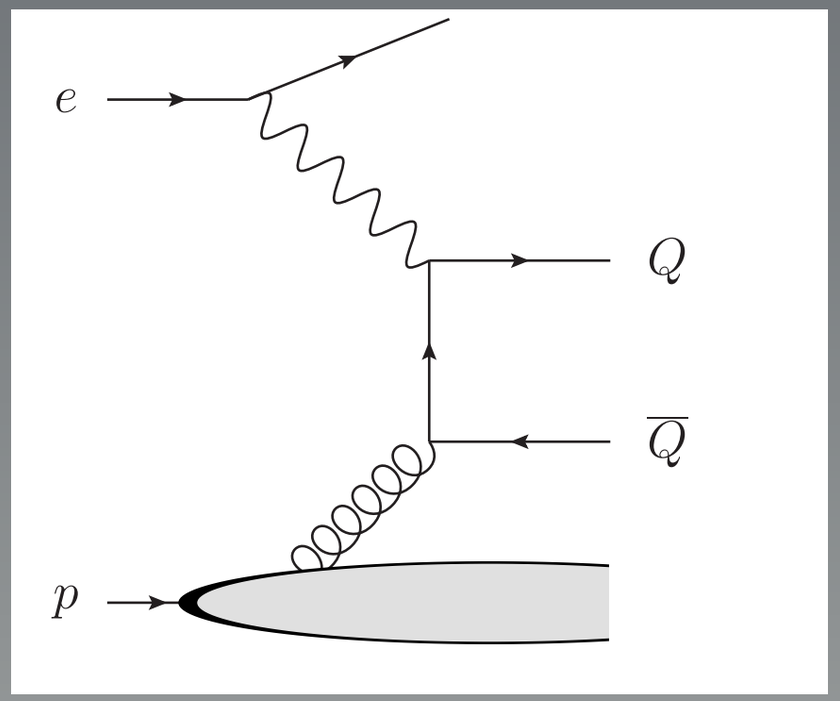
# HEAVY QUARK PAIR IN EP COLLISIONS

D. Boer, P.J. Mulders, C. Pisano, Phys. Rev. D. 80, 094017 (2009); C. Pisano et al., JHEP 1310, 024 (2013)



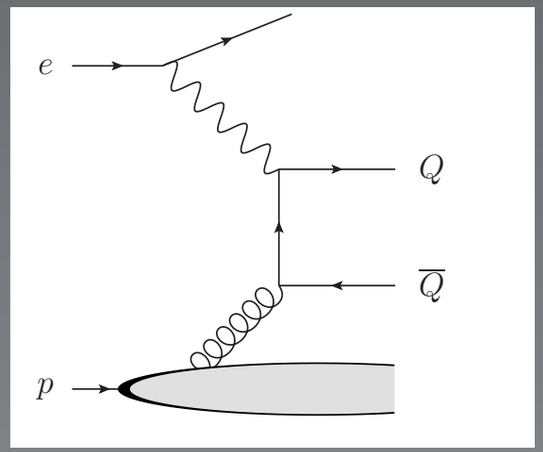
# HEAVY QUARK PAIR IN EP COLLISIONS

D. Boer, P.J. Mulders, C. Pisano, Phys. Rev. D. 80, 094017 (2009); C. Pisano et al., JHEP 1310, 024 (2013)

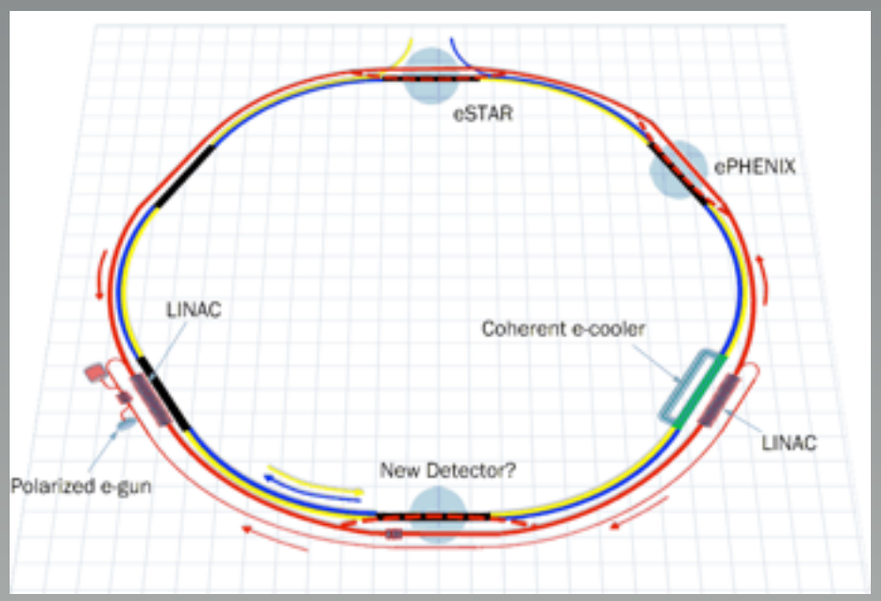



- Gluon distributions appear linearly
- No quark induced background

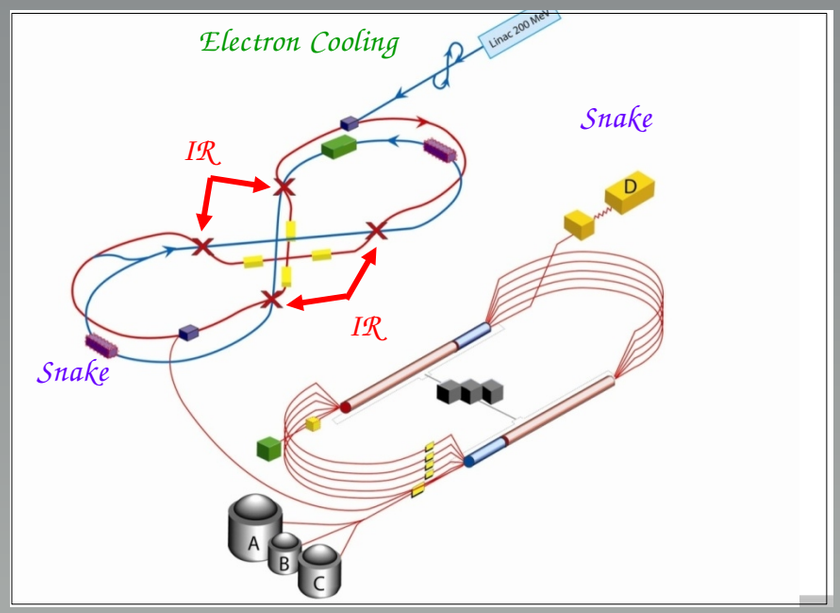
# HEAVY QUARK PAIR IN EP COLLISIONS



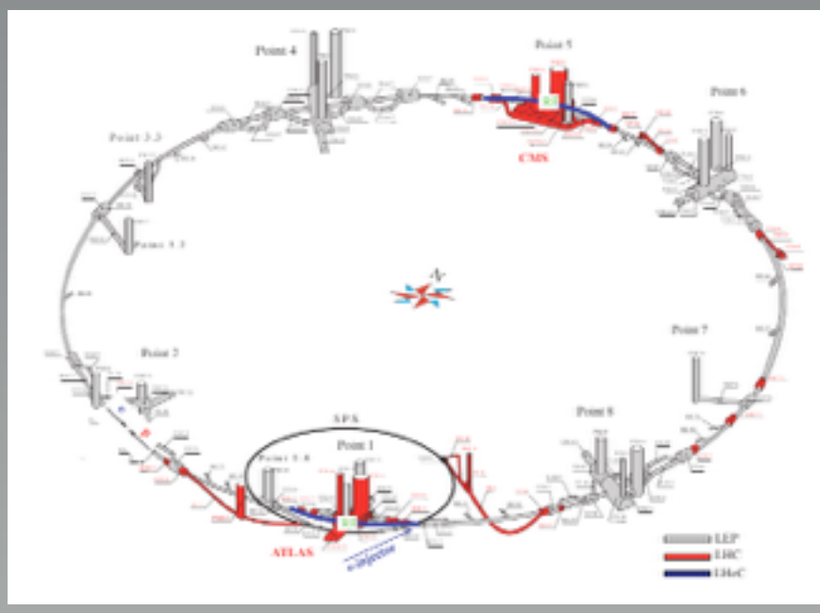

## eRHIC (BNL)?




## ELIC (JLAB)?

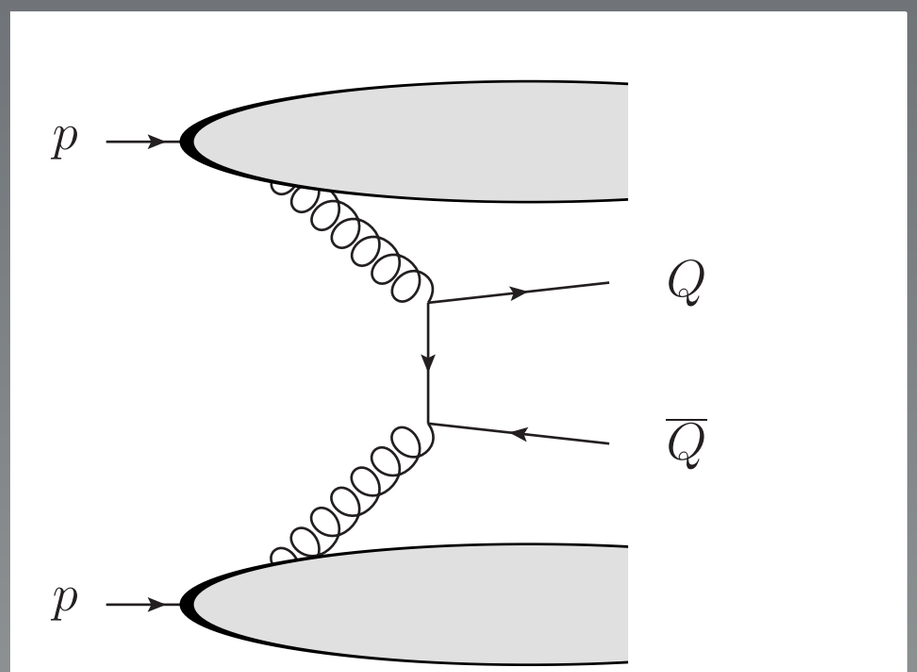



## LHeC (CERN)?



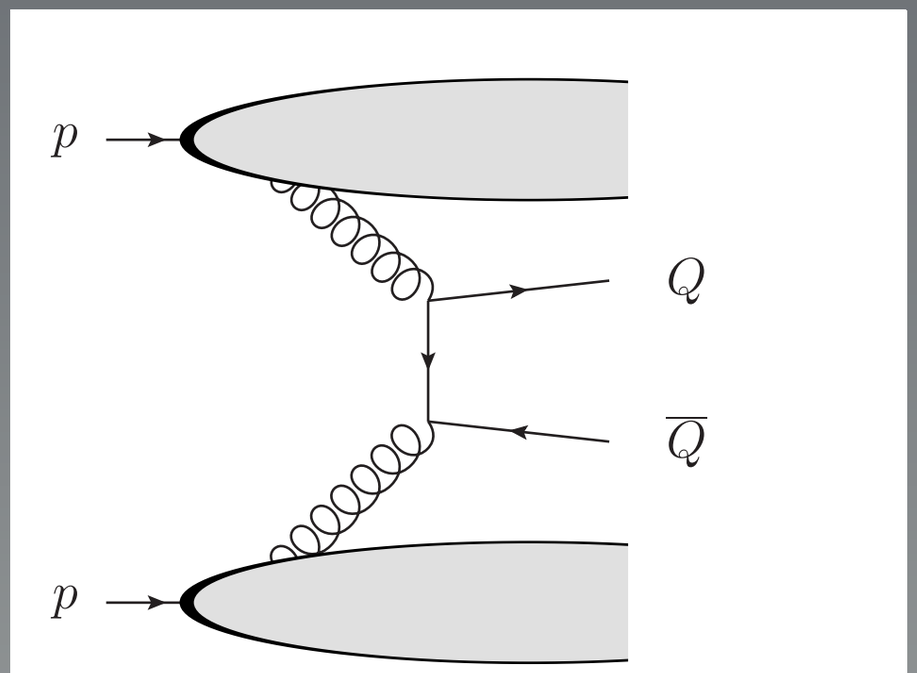
# HEAVY QUARK PAIR IN PP COLLISIONS

D. Boer, P.J. Mulders, C. Pisano, Phys. Rev. D. 80, 094017 (2009); C. Pisano et al., JHEP 1310, 024 (2013)



# HEAVY QUARK PAIR IN PP COLLISIONS

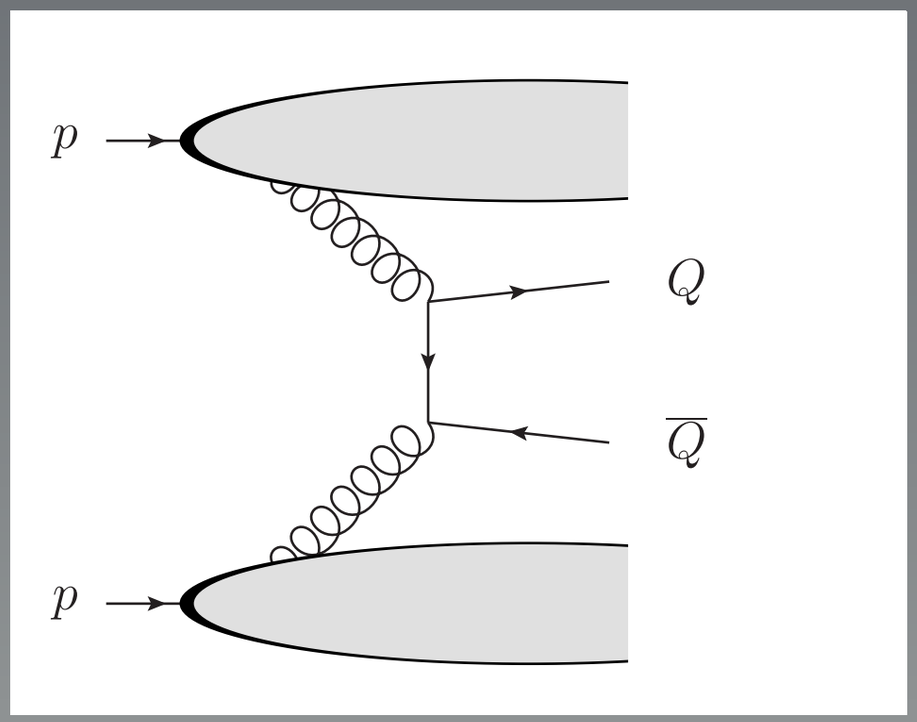
D. Boer, P.J. Mulders, C. Pisano, Phys. Rev. D. 80, 094017 (2009); C. Pisano et al., JHEP 1310, 024 (2013)

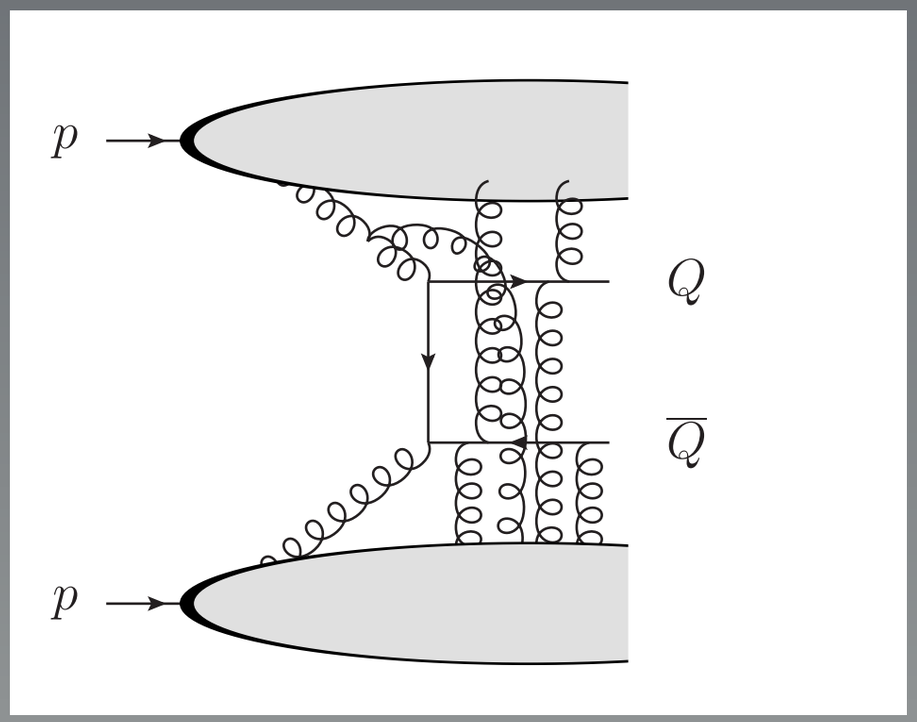



- Measurable at the LHC
- No quark induced background

# HEAVY QUARK PAIR IN PP COLLISIONS

D. Boer, P.J. Mulders, C. Pisano, Phys. Rev. D. 80, 094017 (2009); C. Pisano et al., JHEP 1310, 024 (2013)



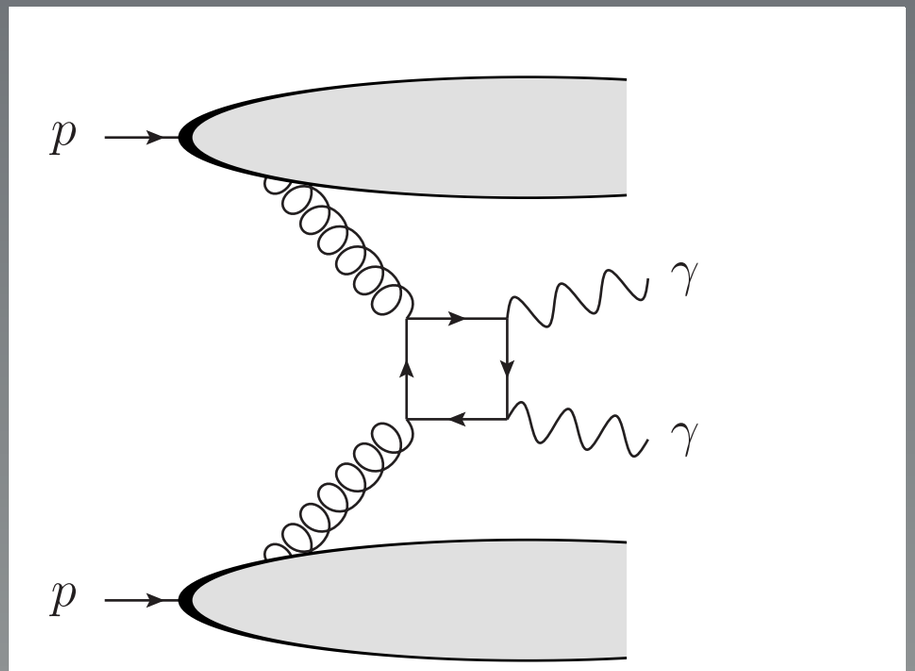




- Measurable at the LHC
- No quark induced background

Does not factorize (at least not in terms of two ‚standard' TMDs)

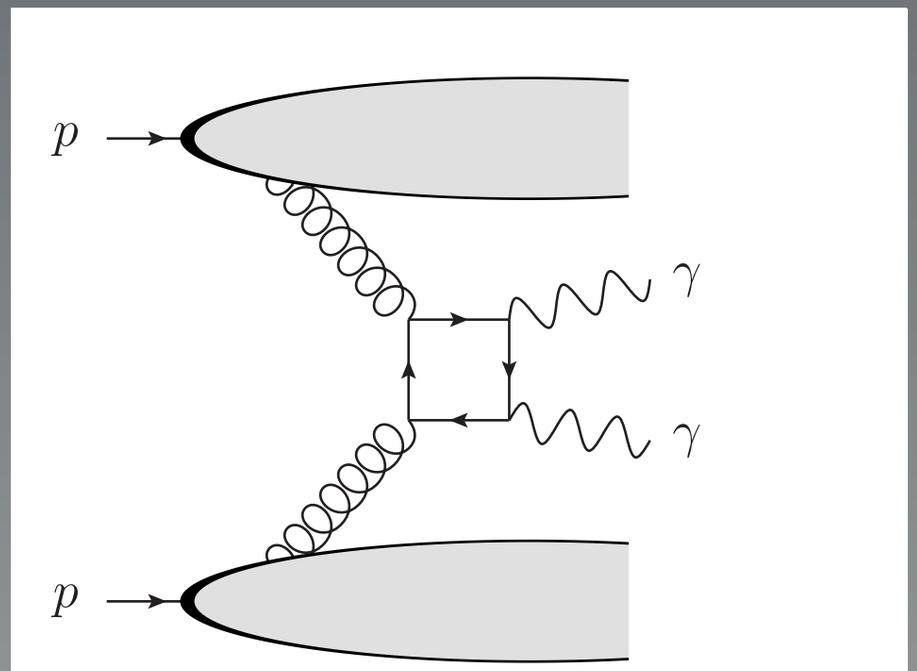
# DIPHOTON IN PP COLLISIONS

J.W. Qiu, M. Schlegel, W. Vogelsang, Phys. Rev. Lett. 107, 062001 (2011)



# DIPHOTON IN PP COLLISIONS

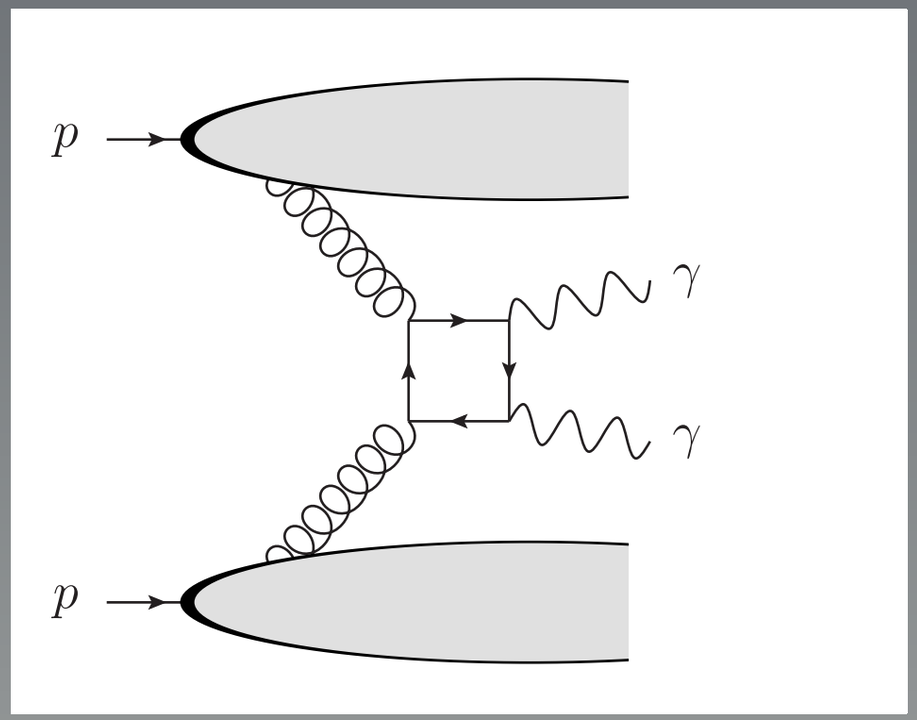
J.W. Qiu, M. Schlegel, W. Vogelsang, Phys. Rev. Lett. 107, 062001 (2011)



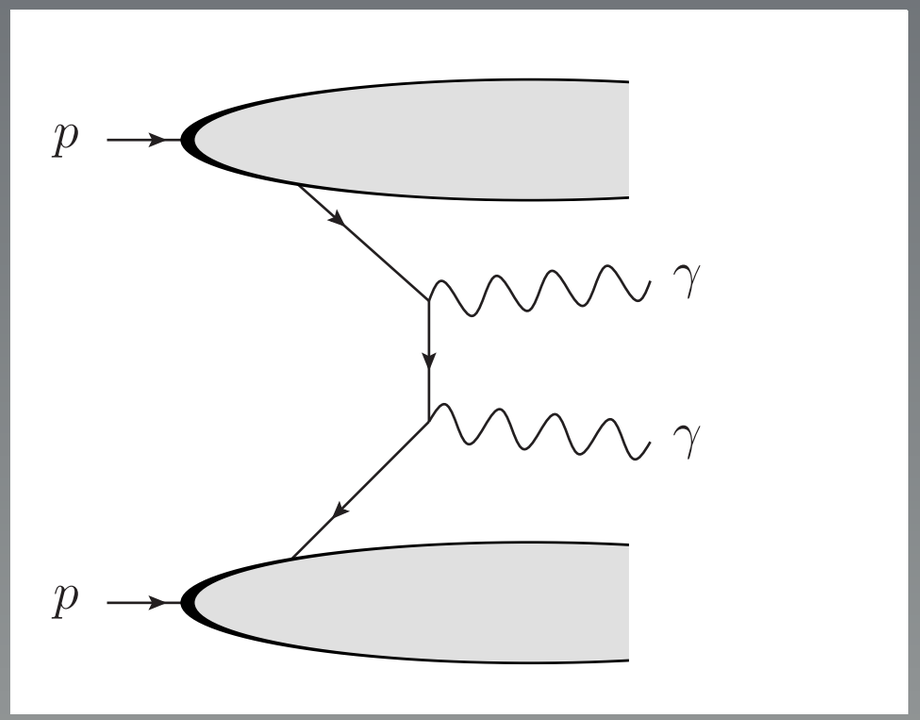

Factorization OK

# DIPHOTON IN PP COLLISIONS

J.W. Qiu, M. Schlegel, W. Vogelsang, Phys. Rev. Lett. 107, 062001 (2011)

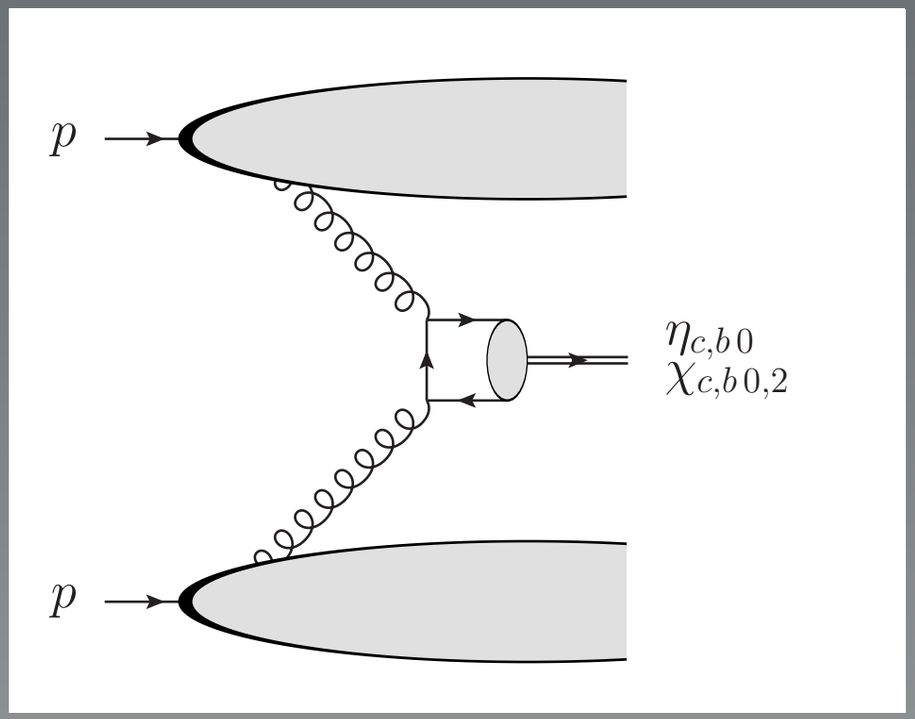



Factorization OK



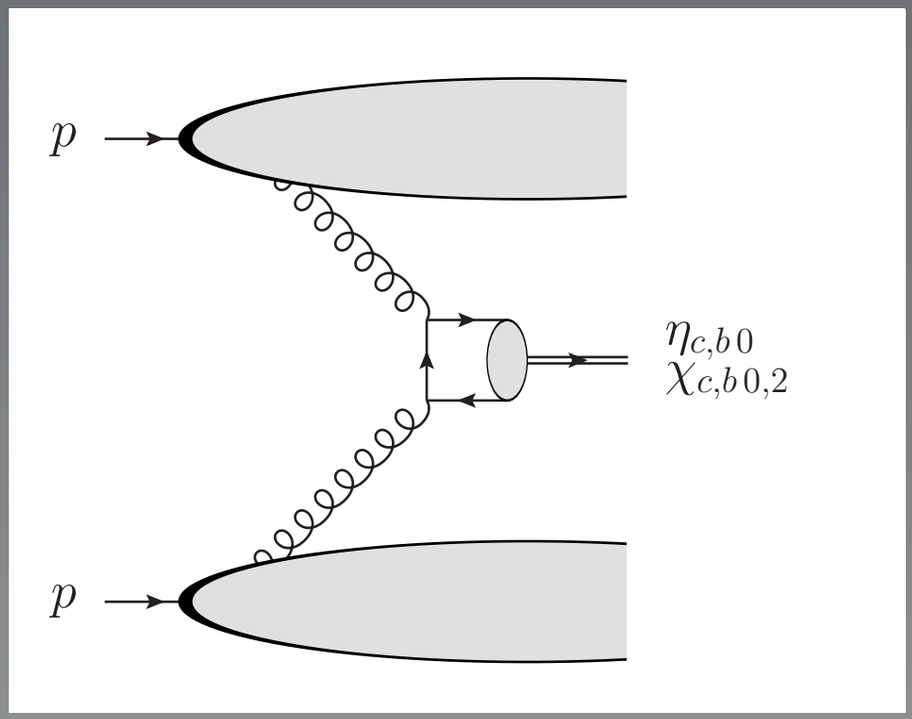

large
quark-antiquark
induced background

# QUARKONIUM IN PP COLLISIONS




D. Boer, C. Pisano, Phys. Rev. D86, 094007 (2012)

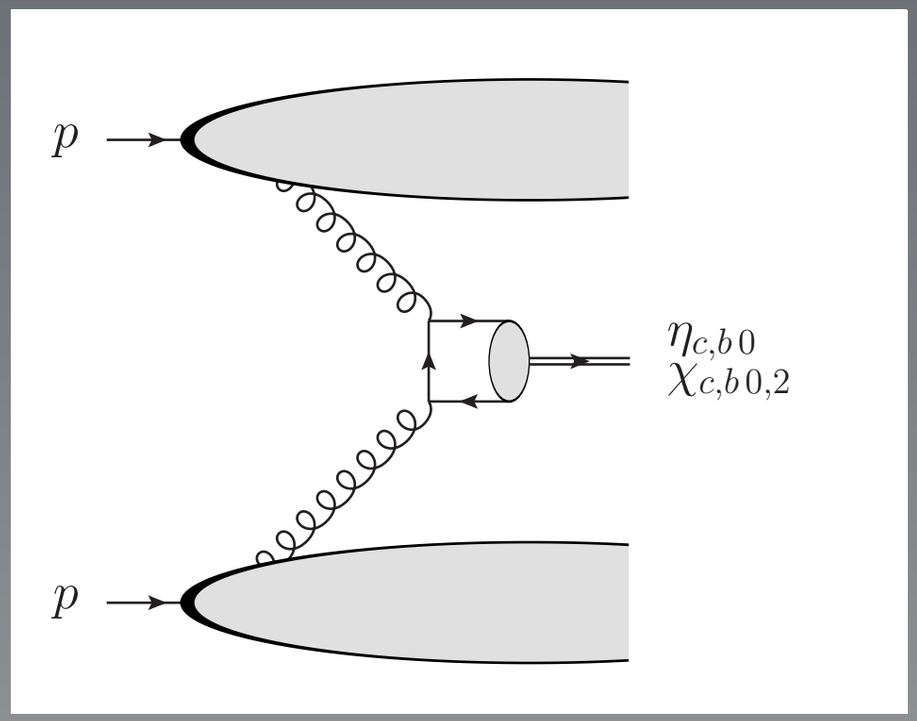
# QUARKONIUM IN PP COLLISIONS




D. Boer, C. Pisano, Phys. Rev. D86, 094007 (2012)

- Factorization OK
- No quark induced background

# QUARKONIUM IN PP COLLISIONS

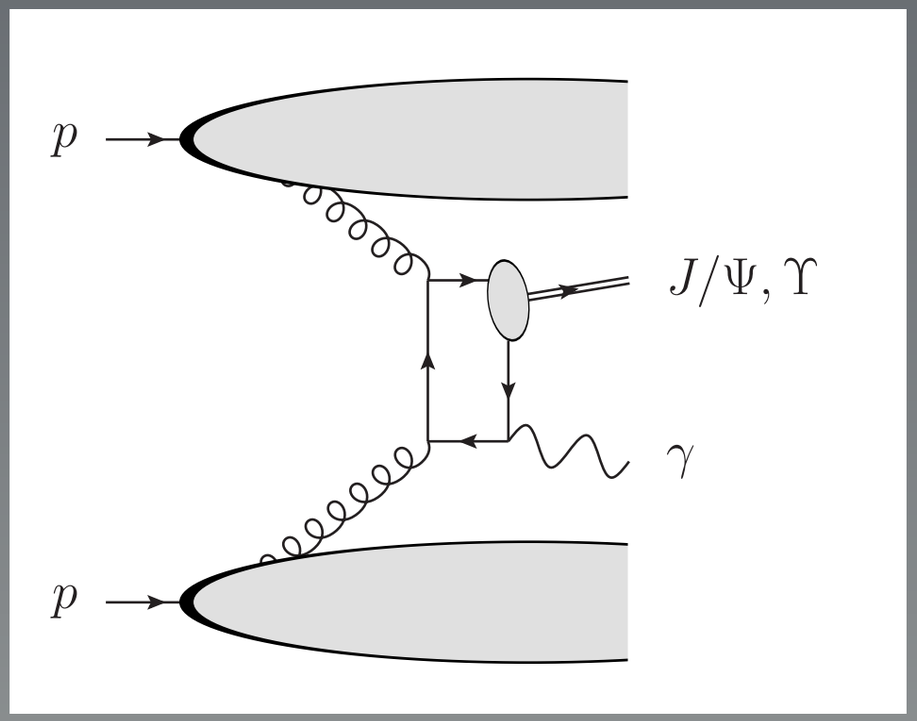



D. Boer, C. Pisano, Phys. Rev. D86, 094007 (2012)

- Factorization OK
- No quark induced background

- Very low Q (limited range of validity)
- Measures $\mathcal{C}[f_1^g f_1^g] \pm \mathcal{C}[w_2\, h_1^{\perp g} h_1^{\perp g}]$
- Relatively difficult to measure

# J/Ψ (or ϒ) + Γ
# IN PP COLLISONS




- Factorization OK
- No quark induced background
- Tuneable Q
- Measurable at ATLAS & CMS
- No mixing of $f_1^g$ & $h_1^{\perp g}$ in $q_T$ distribution

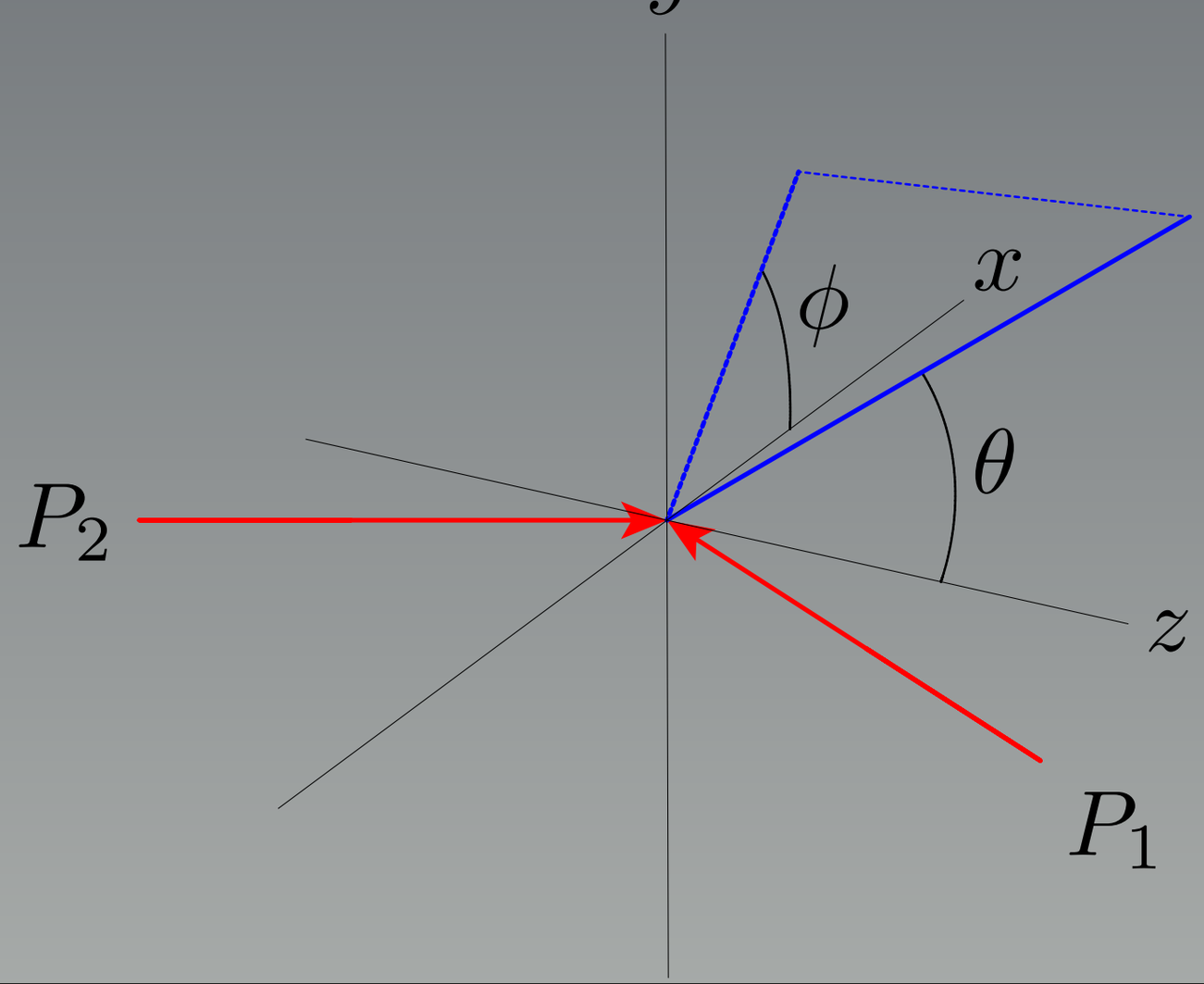
# TMD CROSS SECTION

$$\frac{d\sigma}{d^4q d\Omega} \propto F_1\, \mathcal{C}\Big[f_1^g f_1^g\Big] + F_3\, \mathcal{C}\Big[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\Big] \cos(2\phi) + F_4\, \mathcal{C}\Big[w_4\, h_1^{\perp g} h_1^{\perp g}\Big] \cos(4\phi)$$

$$\begin{aligned}
F_1 &= \big[1 + 2\alpha^2 + 9\alpha^4 + \big(6\alpha^4 - 2\big)\cos^2\theta + \big(\alpha^2 - 1\big)^2 \cos^4\theta)\big]/D \\
F_3 &= \big[4\,\alpha^2\, \sin^2\theta\big]/D \\
F_4 &= \big[\,\big(\alpha^2 - 1\big)^2 \sin^4\theta\big]/D \\
D &= \big[\,\big(\alpha^2 + 1\big)^2 - \big(\alpha^2 - 1\big)^2 \cos^2\theta\big]^2 \\
\alpha &\equiv q^2/M^2
\end{aligned}$$

# TMD CROSS SECTION

$$\frac{d\sigma}{d^4q d\Omega} \propto F_1 \mathcal{C}\Big[f_1^g f_1^g\Big] + F_3 \mathcal{C}\Big[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\Big] \cos(2\phi) + F_4 \mathcal{C}\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big] \cos(4\phi)$$

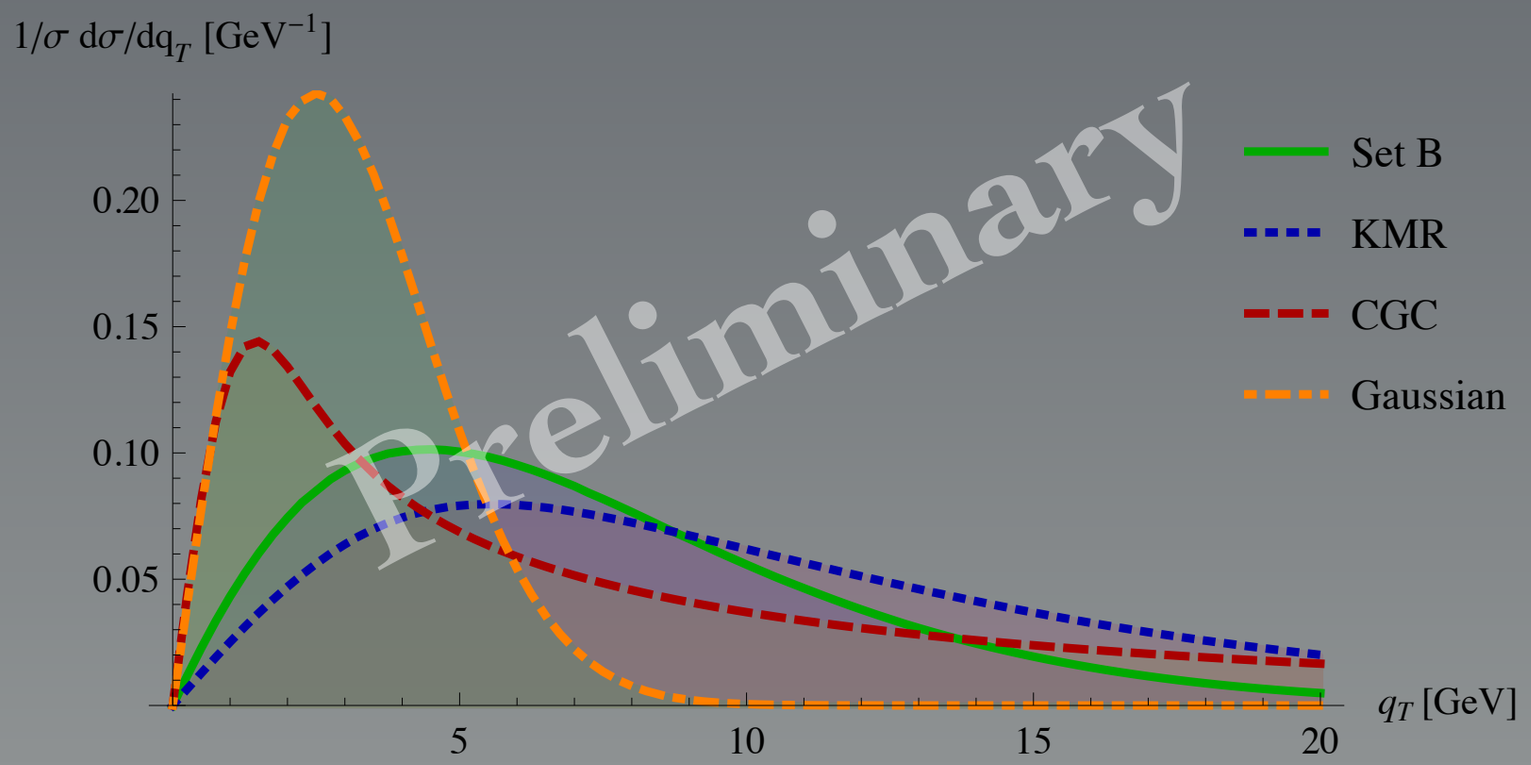


# TMD CROSS SECTION

$$\frac{d\sigma}{d^4q d\Omega} \propto F_1 \mathcal{C}\Big[f_1^g f_1^g\Big] + F_3 \mathcal{C}\Big[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\Big] \cos(2\phi) + F_4 \mathcal{C}\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big] \cos(4\phi)$$

- qT distribution solely depends on unpolarized gluon TMD
- ϕ distribution can be used to determine linearly polarized gluon distribution

# SOME NUMERICAL PREDICTIONS




$Q = 20$ GeV

$Y = 0$

$\theta = \pi/2$

$$\frac{1}{\sigma}\frac{d\sigma^n}{dq_T} \equiv 2|\mathbf{q}_T| \frac{\int_{-\pi}^{\pi} d\phi\, \cos n\phi\, d\sigma}{\int_0^{q_{T\max}^2} dq_T^2 \int_{-\pi}^{\pi} d\phi\, d\sigma}$$

# UGDs IN SMALL-X QCD

Unintegrated Gluon Distribution

- In the Color Glass Condensate model
- As solution to the CCFM equation
- In the BFKL formalism
- ...

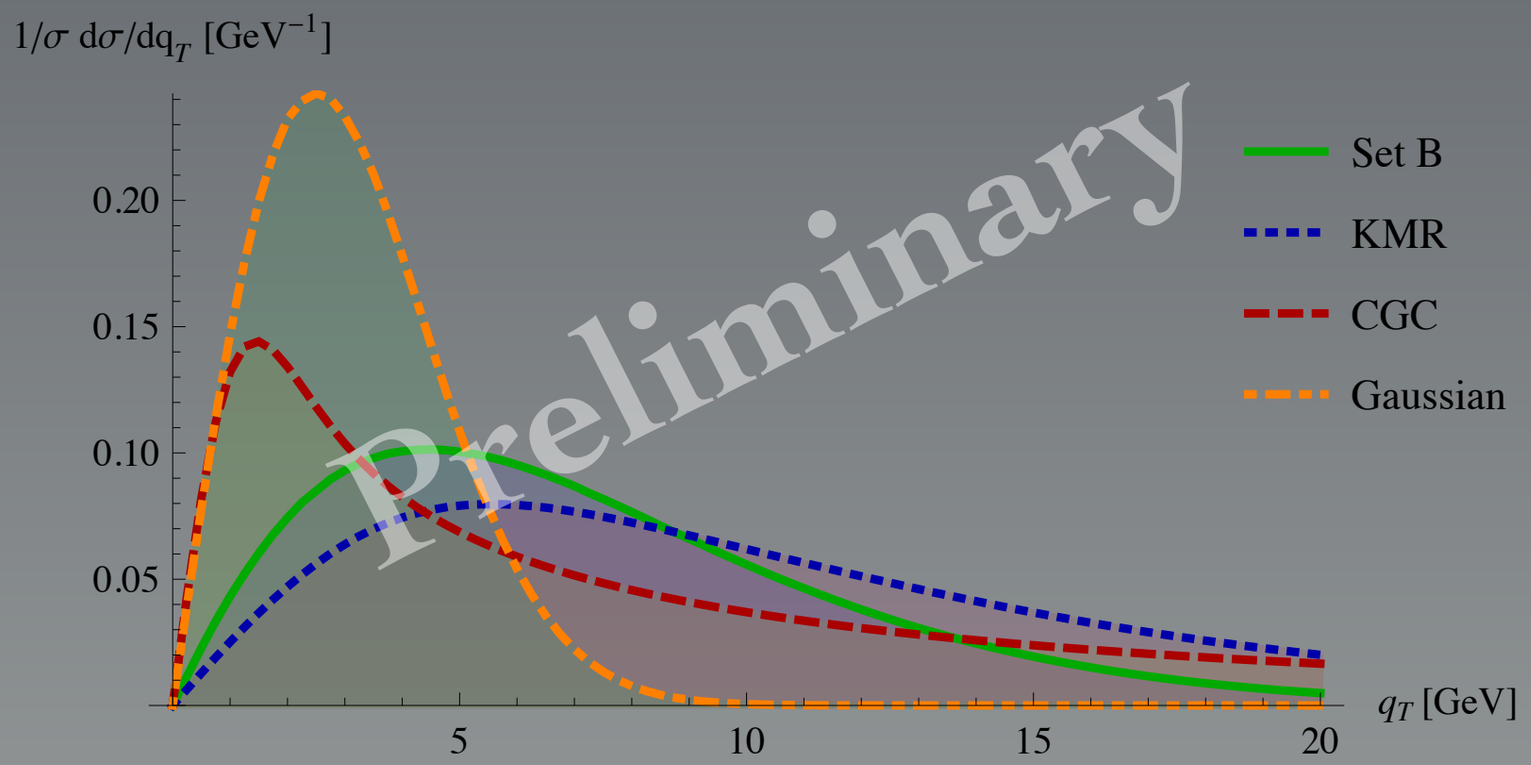
Exact definition not always clear,
for discussion on these issues see e.g.
arXiv:1203.1916 and arXiv:1108.1181

# UGDs IN SMALL-X QCD

... apart from these difficulties,
we think they are a reasonable first Ansatz for our unpolarized TMD distribution

- Set B0 solution to CCFM equation from
  H. Jung, S. Baranov, M. Deak, A. Grebenyuk, F. Hautmann, M. Hentschinski, A. Knutsson and M. Kramer et al., Eur. Phys. J. C 70, 1237 (2010)
- CGC model predictions from
  F. Dominguez, B. -W. Xiao and F. Yuan, Phys. Rev. Lett. 106, 022301 (2011)
  F. Dominguez, C. Marquet, B. -W. Xiao and F. Yuan, Phys. Rev. D 83, 105005 (2011)
  F. Dominguez, J. -W. Qiu, B. -W. Xiao and F. Yuan, Phys. Rev. D 85, 045003 (2012)
  A. Metz and J. Zhou, Phys. Rev. D 84, 051503 (2011)
- KMR parametrization from
  M. A. Kimber, A. D. Martin and M. G. Ryskin, Phys. Rev. D 63, 114027 (2001)

# SOME NUMERICAL PREDICTIONS



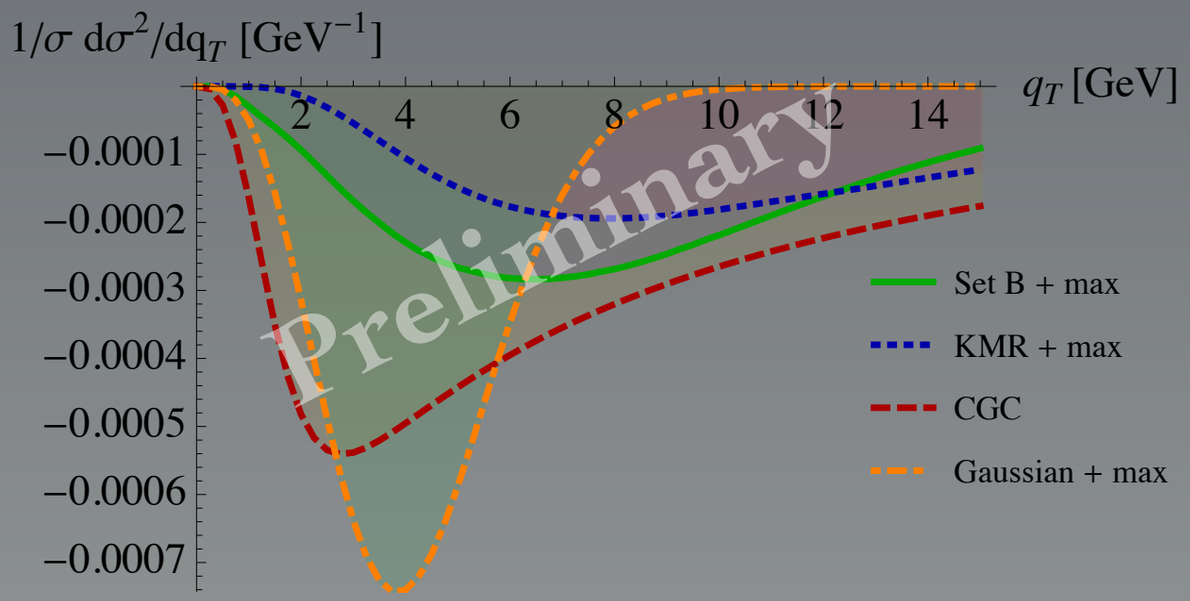

$Q = 20$ GeV

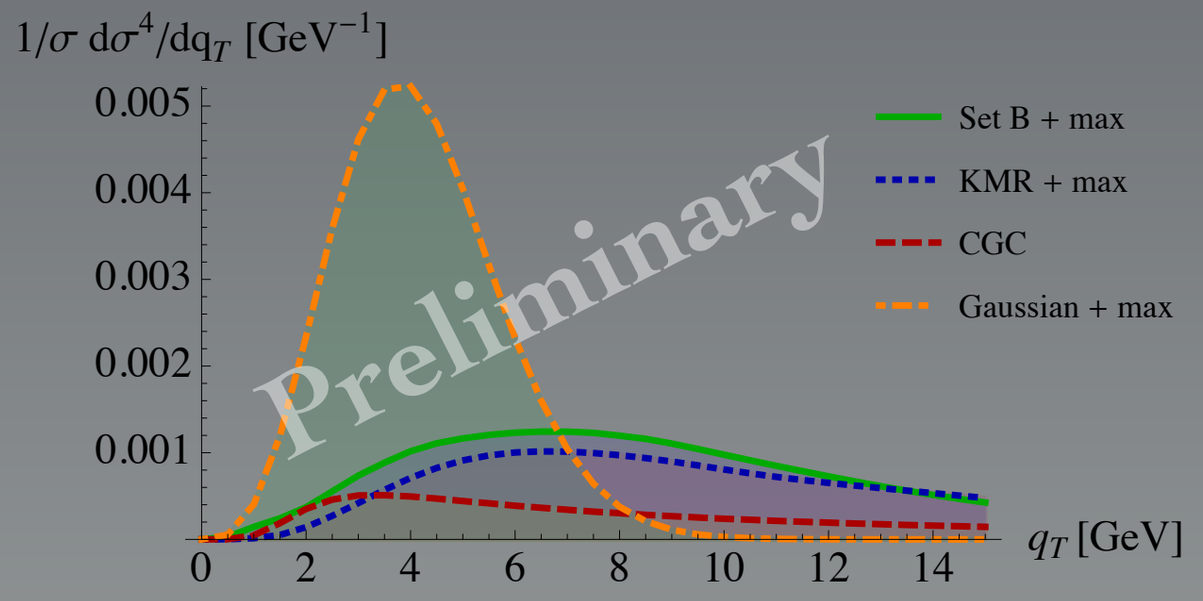
$Y = 0$

$\theta = \pi/2$

$$\frac{1}{\sigma}\frac{d\sigma^n}{dq_T} \equiv 2|\mathbf{q}_T| \frac{\int_{-\pi}^{\pi} d\phi\, \cos n\phi\, d\sigma}{\int_0^{q_{T\max}^2} dq_T^2 \int_{-\pi}^{\pi} d\phi\, d\sigma}$$

# SOME NUMERICAL PREDICTIONS




$$\frac{1}{\sigma}\frac{d\sigma^n}{dq_T} \equiv 2|\mathbf{q}_T|\frac{\int_{-\pi}^{\pi} d\phi\, \cos n\phi\, d\sigma}{\int_0^{q_{T\max}^2} dq_T^2 \int_{-\pi}^{\pi} d\phi\, d\sigma}$$

$$Q = 20\ \mathrm{GeV}$$
$$Y = 0$$
$$\theta = \pi/2$$

# CONCLUSIONS

- TMD factorization consistently takes into account partonic transverse momentum and polarization
- ***Two*** distributions needed to describe a parton in an unpolarized proton
- pQCD calculation indicates large gluon polarization
- Gluon polarization in Higgs production can be used to determine spin & parity
- J/Ψ+γ production good candidate to measure both gluon TMD distributions