# TMD Evolution and the Higgs transverse momentum distribution

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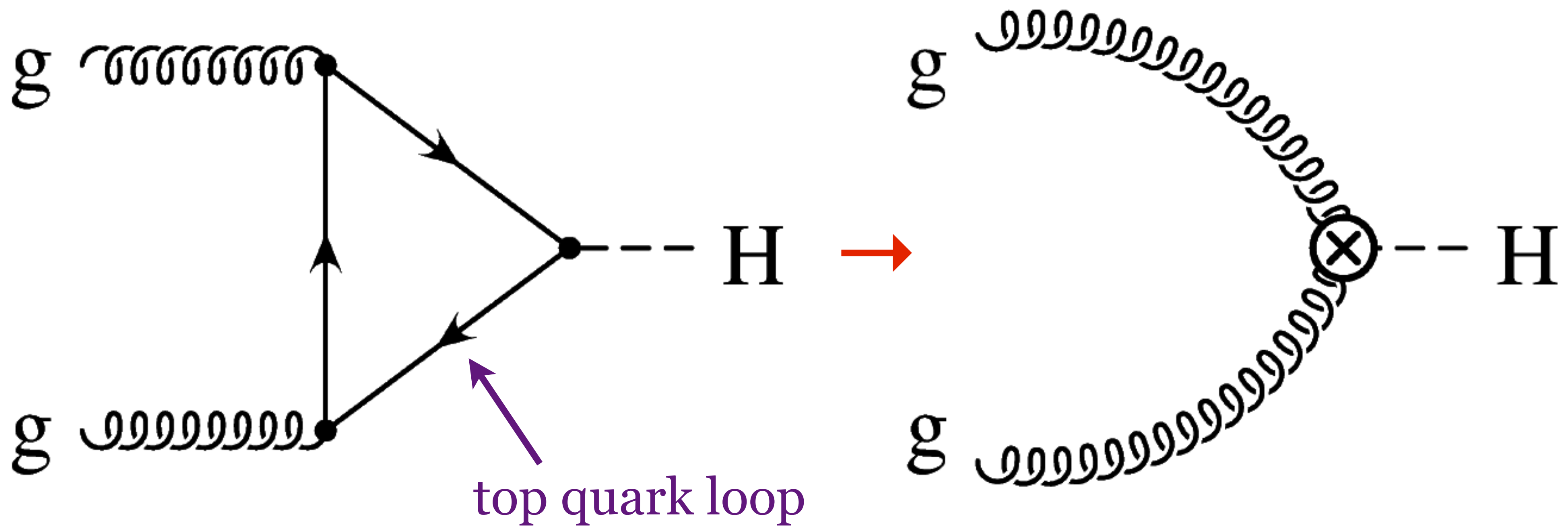
# Outline

- Higgs transverse momentum distribution
- Linear gluon polarization in unpolarized hadrons
- Electron-ion collisions
- Small x aspects

# Higgs transverse momentum distribution

# Higgs production in gluon fusion

Higgs production happens predominantly via gg → H

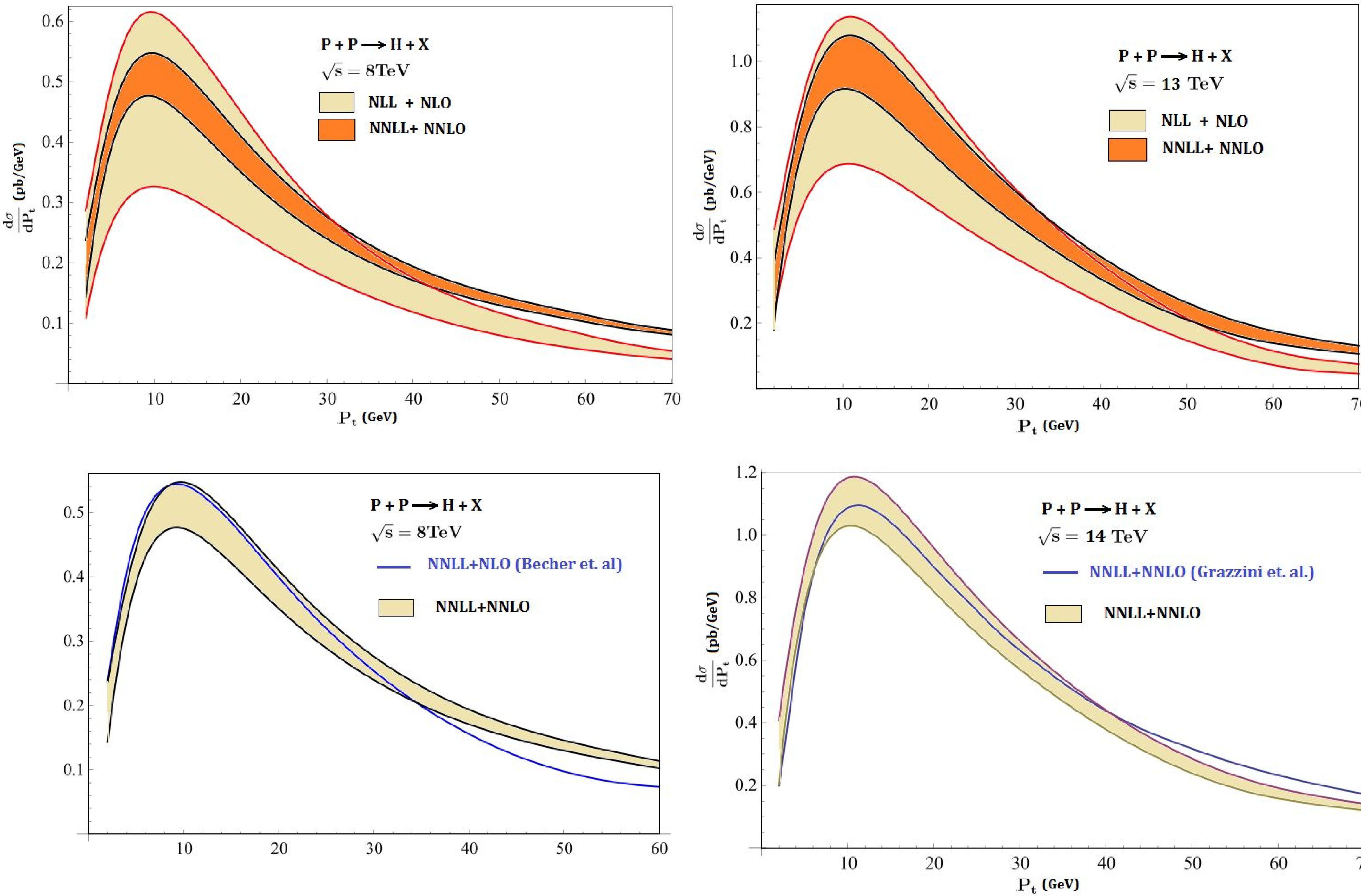



The inclusive Higgs production cross section at LHC can be described well because the collinear gluon distribution inside protons is known well

It becomes a different matter for the transverse momentum distribution
At large $Q_T$ one can again use collinear factorization, but at smaller $Q_T$ there are large logs of $Q_T/m_H$ (resummation) & nonperturbative contributions

It is natural to describe process in terms of transverse momentum dependent gluon distribution functions (TMDs) and TMD factorization & evolution

# Perturbative state-of-the-art




Neill, Rothstein, Vaidya, arXiv:1503.00005

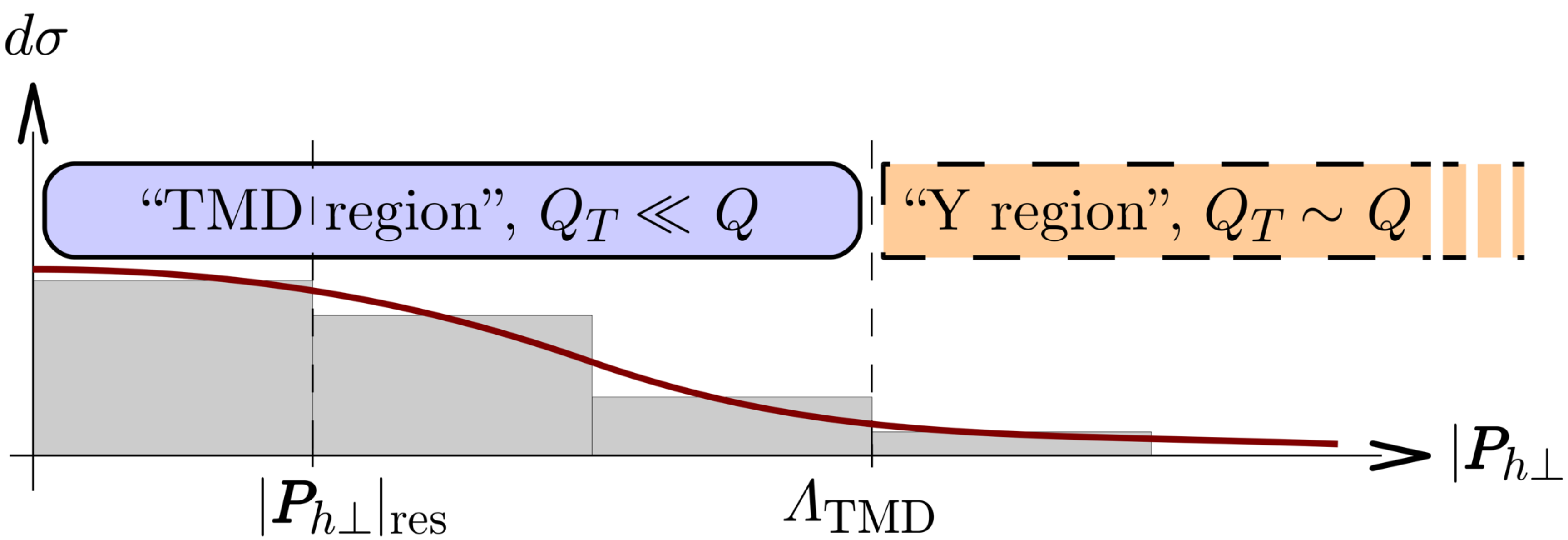
# TMD factorization

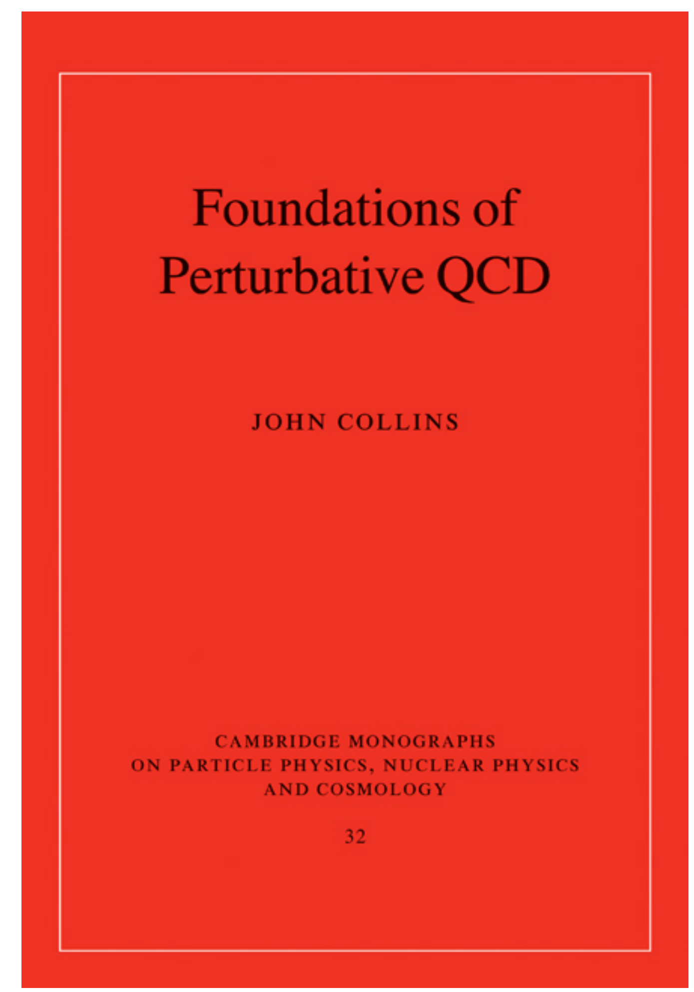
Schematic form of TMD factorization [Collins 2011; Echevarria, Idilbi, Scimemi, 2012]:

$$d\sigma = H \times \text{convolution of } A\,B + \text{high-}q_T \text{ correction } (Y) + \text{power-suppressed}$$

A & B are TMD pdfs or FFs
(a soft factor has been absorbed in them)

Details in book by J.C. Collins
Summarized in arXiv:1107.4123




Convolution in terms of A and B best
deconvoluted by Fourier transform

# TMD factorization expressions

Y term

$$\frac{d\sigma}{d\Omega d^4q} = \int d^2b\, e^{-i\boldsymbol{b}\cdot\boldsymbol{q}_T}\,\tilde{W}(\boldsymbol{b},Q;x,y,z) + \mathcal{O}\left(Q_T^2/Q^2\right)$$

$$\tilde{W}(\boldsymbol{b},Q;x_A,x_B) = \tilde{f}_1^g(x_A,\boldsymbol{b}^2;\zeta_A,\mu)\,\tilde{f}_1^g(x_B,\boldsymbol{b}^2;\zeta_B,\mu)H(Q;\mu)$$

Fourier transforms of the TMDs are functions of the momentum fraction *x*, the transverse coordinate ***b***, a rapidity variable ζ , and the renormalization scale μ

$$\zeta_A = M_A^2 x_A^2 e^{2(y_A - y_s)} \qquad \zeta_B = M_B^2 x_B^2 e^{2(y_s - y_B)}$$

$y_s$ is an arbitrary rapidity that drops out of the final answer

$$\zeta_A\zeta_B \approx Q^4 \qquad\qquad \zeta_A \approx \zeta_B \approx Q^2$$

The TMDs in principle also depend on a process dependent Wilson line $U$

$$\tilde{f}^{[\mathcal{U}]}(x, b_T^2; \zeta, \mu)$$

# TMD factorization expressions

$$\frac{d\sigma}{d\Omega d^4q} = \int d^2b \, e^{-i\boldsymbol{b}\cdot\boldsymbol{q}_T} \tilde{W}(\boldsymbol{b}, Q; x, y, z) + \mathcal{O}\left(Q_T^2/Q^2\right)$$

$$\tilde{W}(\boldsymbol{b}, Q; x_A, x_B) = \tilde{f}_1^g(x_A, \boldsymbol{b}^2; \zeta_A, \mu)\, \tilde{f}_1^g(x_B, \boldsymbol{b}^2; \zeta_B, \mu) H\left(Q; \mu\right)$$

Take $\mu = Q$

$$H\left(Q; \alpha_s(Q)\right) \propto e_a^2 \left(1 + \alpha_s(Q^2) F_1 + \mathcal{O}(\alpha_s^2)\right)$$

This choice avoids large logarithms in H, but now they will appear in the TMDs

Use renormalization group equations to evolve the TMDs to the scale:

$$\mu_b = C_1/b = 2e^{-\gamma_E}/b \quad (C_1 \approx 1.123)$$

This resums large logs in bQ

So even at one value of Q one probes TMDs at a whole range of scales

# Resummation of large logs

$$
\begin{aligned}
\mathcal{C}\left[f_1^g\, f_1^g\right] &= \int \frac{d^2\boldsymbol{b}}{(2\pi)^2}\, e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T}\, \tilde{f}_1^g(x_A, b^2; \zeta_A, Q)\, \tilde{f}_1^g(x_B, b^2; \zeta_B, Q) \\
&= \int \frac{d^2\boldsymbol{b}}{(2\pi)^2}\, e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T}\, e^{-S_A(b,Q)}\, \tilde{f}_1^g(x_A, b^2; \mu_b^2, \mu_b)\, \tilde{f}_1^g(x_B, b^2; \mu_b^2, \mu_b)
\end{aligned}
$$

Perturbative Sudakov factor:

$$
\begin{aligned}
S_A(b,Q) &= \frac{C_A}{\pi}\int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\alpha_s(\mu)\left[\ln\left(\frac{Q^2}{\mu^2}\right) - \frac{11 - 2n_f/C_A}{6}\right] + \mathcal{O}(\alpha_s^2) \\
&= -\frac{36}{33-2n_f}\left[\ln\left(\frac{Q^2}{\mu_b^2}\right) + \ln\left(\frac{Q^2}{\Lambda^2}\right)\,\ln\left(1 - \frac{\ln\left(Q^2/\mu_b^2\right)}{\ln\left(Q^2/\Lambda^2\right)}\right)\right. \\
&\qquad \left. + \frac{11 - 2n_f/C_A}{6}\ln\left(\frac{\ln\left(Q^2/\Lambda^2\right)}{\ln\left(\mu_b^2/\Lambda^2\right)}\right)\right]
\end{aligned}
$$

# Nonperturbative Sudakov factor

$$\frac{d\sigma}{dx_A dx_B d\Omega d^2\boldsymbol{q}_T} = \int d^2b\, e^{-i\boldsymbol{b}\cdot\boldsymbol{q}_T} \tilde{W}(\boldsymbol{b}, Q; x_A, x_B) + \mathcal{O}\left(\frac{Q_T^2}{Q^2}\right)$$

The integral is over all b, including large (=nonperturbative) b values

$$\tilde{W}(b) \equiv \tilde{W}(b_*)\, e^{-S_{NP}(b)} \qquad b_* = b/\sqrt{1 + b^2/b_{\max}^2} \leq b_{\max}$$

$$b_{\max} = 1.5 \text{ GeV}^{-1} \Rightarrow \alpha_s(b_0/b_{\max}) = 0.62$$

$W(b_*)$ *can* be calculated within perturbation theory

In general the nonperturbative Sudakov factor is Q dependent

No extraction of $S_{NP}$ exists; use a modified quark one (Drell-Yan), e.g.

$$S_{NP}(b, Q, Q_0) = \frac{C_A}{C_F}\left[0.184 \ln\frac{Q}{2Q_0} + 0.332\right] b^2$$

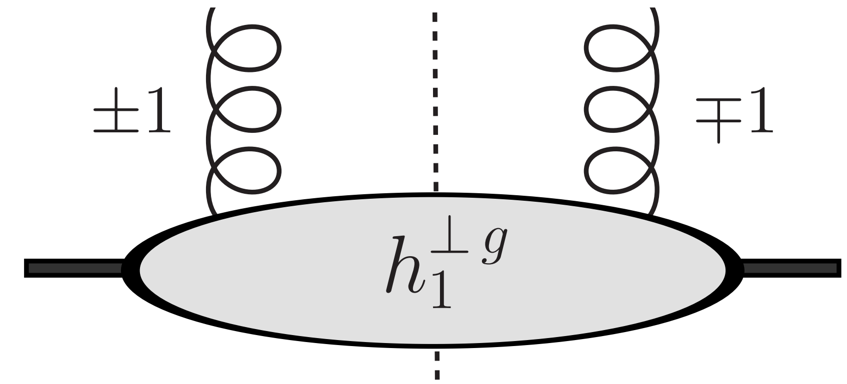
Aybat & Rogers, PRD 83 (2011) 114042

# Effect of gluon polarization on Higgs $Q_T$ distribution

# Gluon polarization inside unpolarized protons

Linearly polarized gluons exist in unpolarized hadrons

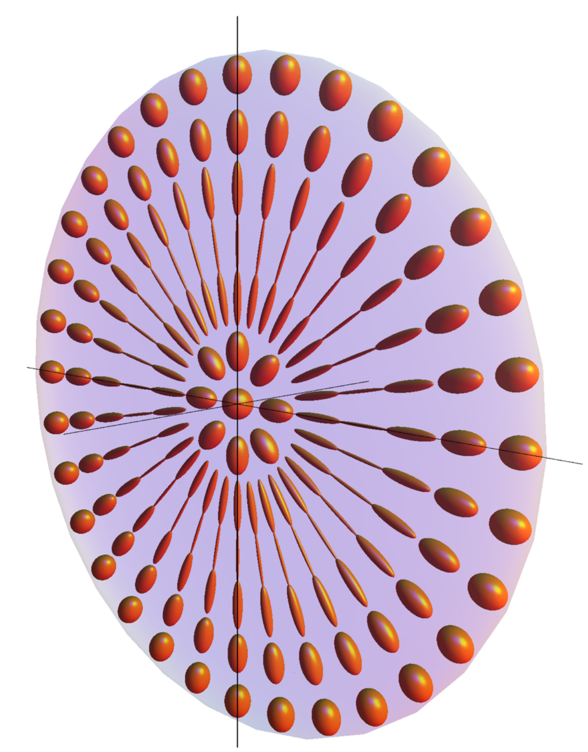
Mulders, Rodrigues, 2001




an interference between
±1 helicity gluon states

It requires nonzero transverse momentum: TMD

For $h_1^{\perp\, g} > 0$ gluons prefer to be polarized along $k_T$, with a $cos\ 2\phi$ distribution of linear polarization around it, where $\phi = \angle(k_T, \varepsilon_T)$



It affects the transverse momentum distribution in $pp \to HX$ (Higgs production)

Catani & Grazzini, 2010; Sun, Xiao, Yuan, 2011; D.B., Den Dunnen, Pisano, Schlegel, Vogelsang, 2012

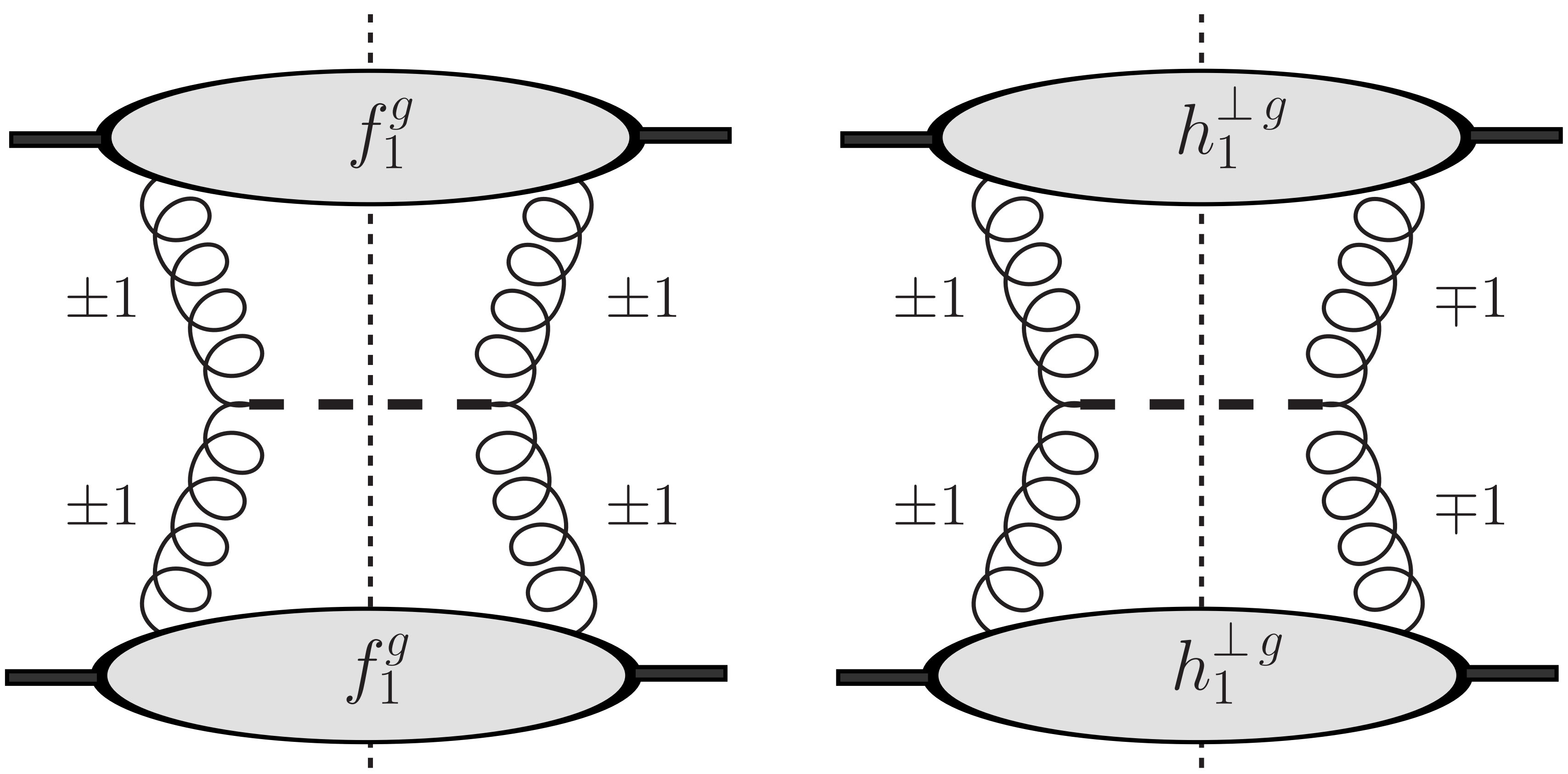
# Higgs transverse momentum

Linearly polarized gluons are generated perturbatively
[Nadolsky, Balazs, Berger, Yuan, 2007]

Linearly polarized gluons enter Higgs production ($\sigma(Q_T)$) at NNLO pQCD
[Catani & Grazzini, 2010]

The nonperturbative distribution can be present at tree level and would affect Higgs production at low $Q_T$

[Sun, Xiao, Yuan, 2011; DB, Den Dunnen, Pisano, Schlegel, Vogelsang, 2012]



# $h_1^{\perp g}$ in $p\,p \to H\;X$

$$\frac{d\sigma}{dx_A dx_B d\Omega d^2\boldsymbol{q}_T} = \int d^2b\, e^{-i\boldsymbol{b}\cdot\boldsymbol{q}_T}\,\tilde{W}(\boldsymbol{b},Q;x_A,x_B) + \mathcal{O}\left(\frac{Q_T^2}{Q^2}\right)$$

$$\tilde{W}(\boldsymbol{b},Q;x_A,x_B) = \tilde{f}_1^g(x_A,\boldsymbol{b}^2;\zeta_A,\mu)\,\tilde{f}_1^g(x_B,\boldsymbol{b}^2;\zeta_B,\mu)H(Q;\mu)$$

Linearly polarized gluons inside unpolarized protons adds a term to W(b)

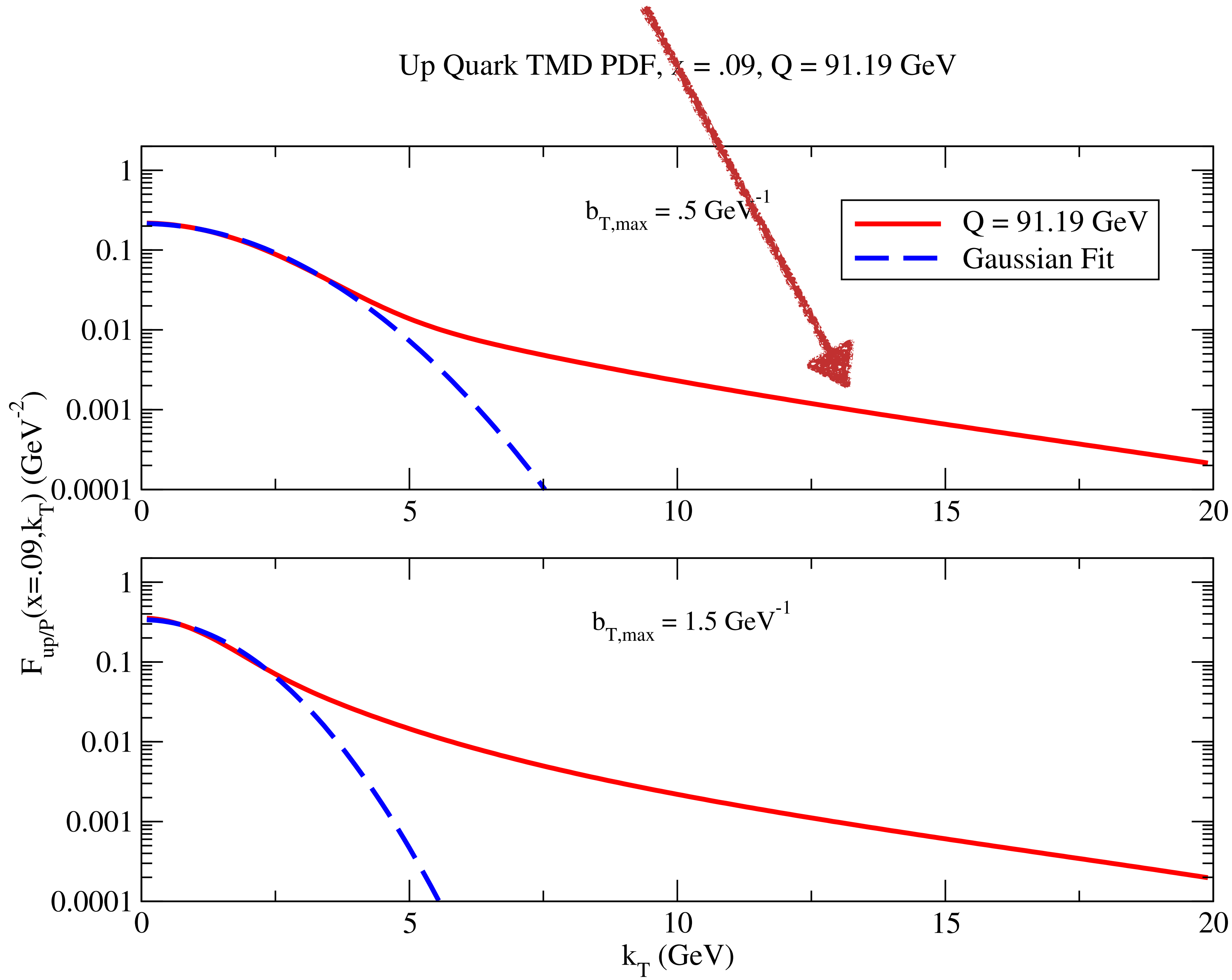
$$\tilde{\Phi}_g^{ij}(x,\boldsymbol{b}) = \frac{1}{2x}\left\{\delta^{ij}\,\tilde{f}_1^g(x,b^2) - \left(\frac{2b^ib^j}{b^2} - \delta^{ij}\right)\tilde{h}_1^{\perp\,g}(x,b^2)\right\}$$

$$\begin{aligned}\Phi_g^{\mu\nu}(x,\boldsymbol{p}_T) &= \frac{n_\rho\,n_\sigma}{(p\cdot n)^2}\int\frac{d(\xi\cdot P)\,d^2\xi_T}{(2\pi)^3}\;e^{ip\cdot\xi}\,\langle P|\,\mathrm{Tr}\big[\,F^{\mu\rho}(0)\,F^{\nu\sigma}(\xi)\,\big]\,|P\rangle\,\big]_{\mathrm{LF}} \\ &= -\frac{1}{2x}\left\{g_T^{\mu\nu}\,f_1^g - \left(\frac{p_T^\mu p_T^\nu}{M^2} + g_T^{\mu\nu}\frac{\boldsymbol{p}_T^2}{2M^2}\right)h_1^{\perp\,g}\right\}\end{aligned}$$

This term requires nonzero $k_T$, but is $k_T$ even, chiral even and T even

# Large $k_T$ tail

Under evolution, TMDs develop a power law tail



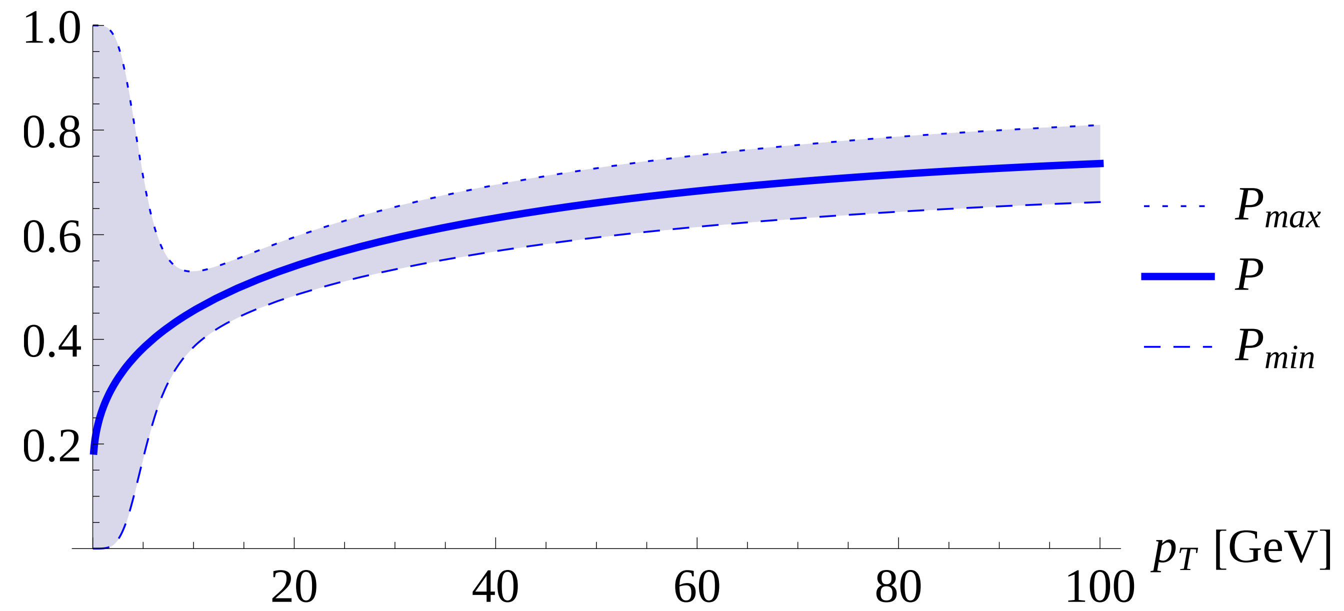

Aybat & Rogers, PRD 83 (2011) 114042

The large $k_T$ tail can be calculated perturbatively: $\sim \alpha_s/k_T^2$

# Moving to b space

Amount of linear gluon polarization:

D.B., Den Dunnen, Pisano, Schlegel '13




Ratio of large $k_T$ tails of $h_1^{\perp}$ and $f_1$ is large, does not mean large effects at large $Q_T$ (which involves ratios of *integrals* over all $k_T$)

What matters is the small b behavior of the Fourier transformed TMD:

$$\tilde{f}_1^g(x, b^2; \mu_b^2, \mu_b) = f_{g/P}(x; \mu_b) + \mathcal{O}(\alpha_s)$$

$$\tilde{h}_1^{\perp g}(x, b^2; \mu_b^2, \mu_b) = \frac{\alpha_s(\mu_b) C_A}{2\pi} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1\right) f_{g/P}(\hat{x}; \mu_b) + \mathcal{O}(\alpha_s^2)$$

[Nadolsky, Balazs, Berger, C.-P. Yuan, 2007; Catani, Grazzini, 2010; P. Sun, B.-W. Xiao, F. Yuan, 2011]

The linear polarization starts at order $\alpha_s$, which gives it a suppression w.r.t. $f_1$

# Full cross section

$$\frac{E\, d\sigma^{pp\to HX}}{d^3\vec{q}}\bigg|_{q_T\ll m_H} = \frac{\pi\sqrt{2}G_F}{128 m_H^2 s}\left(\frac{\alpha_s}{4\pi}\right)^2 |\mathcal{A}_H(\tau)|^2$$
$$\times\left(\mathcal{C}\left[f_1^g\, f_1^g\right] + \mathcal{C}\left[w_H\, h_1^{\perp g}\, h_1^{\perp g}\right]\right) + \mathcal{O}\left(\frac{q_T}{m_H}\right)$$

$$w_H = \frac{(\boldsymbol{p}_T\cdot\boldsymbol{k}_T)^2 - \frac{1}{2}\boldsymbol{p}_T^2\boldsymbol{k}_T^2}{2M^4} \qquad \tau = m_H^2/(4m_t^2)$$

The *angular independent* relative effect of linearly polarized gluons:

$$\mathcal{R}(Q_T) \equiv \frac{\mathcal{C}[w_H\, h_1^{\perp g}\, h_1^{\perp g}]}{\mathcal{C}[f_1^g\, f_1^g]}$$

$$\mathcal{R}(Q_T) = \frac{\int d^2\boldsymbol{b}\, e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T}\, e^{-S_A(b_*,Q)-S_{NP}(b,Q)}\ \tilde{h}_1^{\perp g}(x_A, b_*^2;\mu_{b_*}^2,\mu_{b_*})\ \tilde{h}_1^{\perp g}(x_B, b_*^2;\mu_{b_*}^2,\mu_{b_*})}{\int d^2\boldsymbol{b}\, e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T}\ e^{-S_A(b_*,Q)-S_{NP}(b,Q)}\,\tilde{f}_1^g(x_A, b_*^2;\mu_{b_*}^2,\mu_{b_*})\ \tilde{f}_1^g(x_B, b_*^2;\mu_{b_*}^2,\mu_{b_*})}$$

# Tail-only result

$$\mathcal{R}(Q_T) = \frac{\int d^2\boldsymbol{b}\, e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T} e^{-S_A(b_*,Q)-S_{NP}(b,Q)}\ \tilde{h}_1^{\perp g}(x_A, b_*^2; \mu_{b_*}^2, \mu_{b_*})\ \tilde{h}_1^{\perp g}(x_B, b_*^2; \mu_{b_*}^2, \mu_{b_*})}{\int d^2\boldsymbol{b}\, e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T}\ e^{-S_A(b_*,Q)-S_{NP}(b,Q)}\, \tilde{f}_1^g(x_A, b_*^2; \mu_{b_*}^2, \mu_{b_*})\ \tilde{f}_1^g(x_B, b_*^2; \mu_{b_*}^2, \mu_{b_*})}$$

$$\begin{aligned} \tilde{h}_1^{\perp\, g}(x, b^2) &= \int d^2\boldsymbol{p}_T\ \frac{(\boldsymbol{b}\cdot\boldsymbol{p}_T)^2 - \frac{1}{2}\boldsymbol{b}^2\boldsymbol{p}_T^2}{b^2 M^2}\ e^{-i\boldsymbol{b}\cdot\boldsymbol{p}_T}\ h_1^{\perp g}(x, p_T^2) \\ &= -\pi \int dp_T^2 \frac{p_T^2}{2M^2} J_2(bp_T) h_1^{\perp g}(x, p_T^2) \end{aligned}$$

Consider now only the perturbative tails:

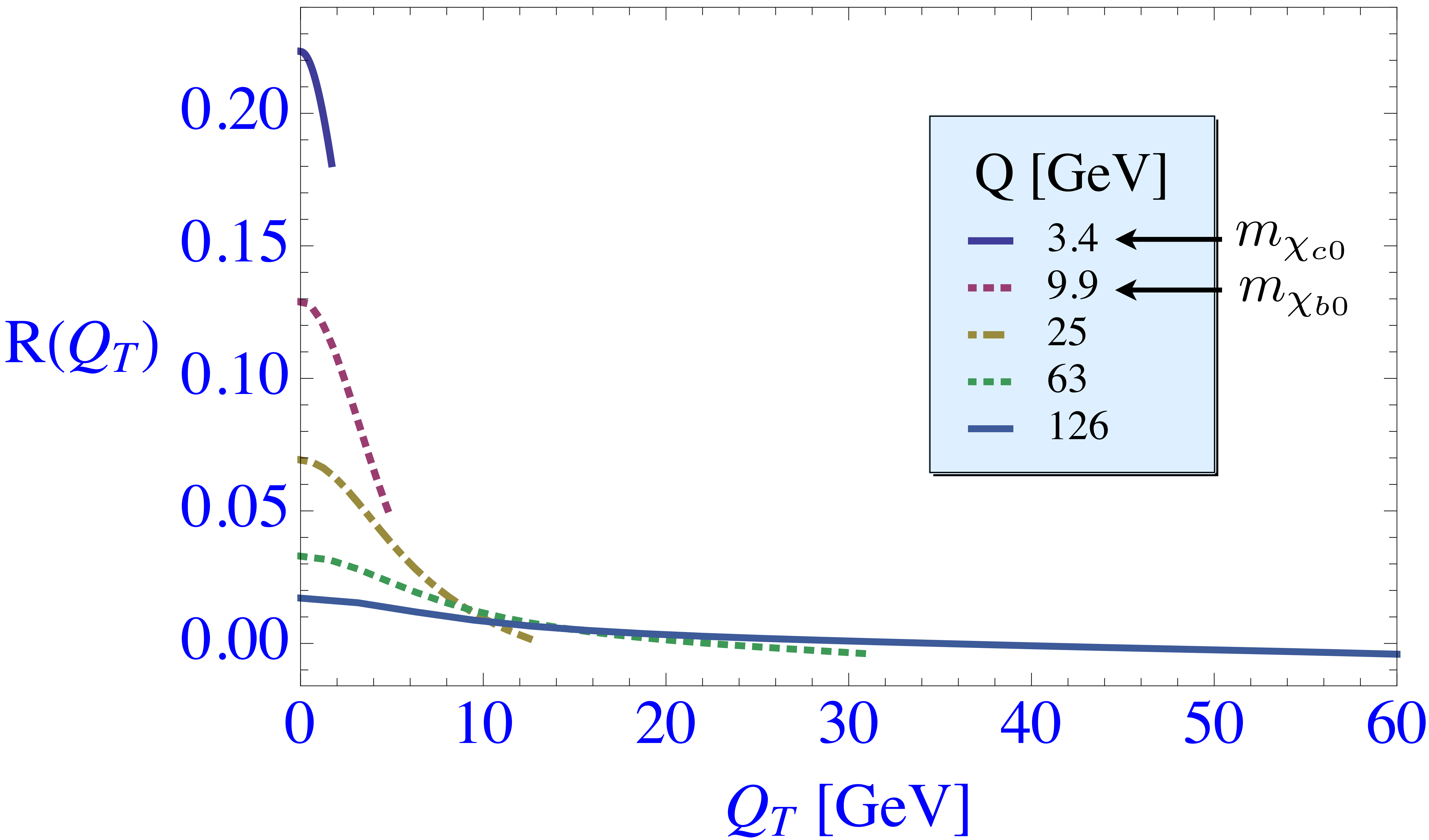
$$\tilde{f}_1^g(x, b^2; \mu_b^2, \mu_b) = f_{g/P}(x; \mu_b) + \mathcal{O}(\alpha_s)$$

$$\tilde{h}_1^{\perp g}(x, b^2; \mu_b^2, \mu_b) = \frac{\alpha_s(\mu_b) C_A}{2\pi} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1\right) f_{g/P}(\hat{x}; \mu_b) + \mathcal{O}(\alpha_s^2)$$

This coincides with the CSS approach

[Nadolsky, Balazs, Berger, C.-P. Yuan, '07; Catani, Grazzini, '10; P. Sun, B.-W. Xiao, F. Yuan, '11]

# TMD evolution




$x_A = x_B = Q/(8\mathrm{TeV})$

$Q^{-0.85}$

MSTW08 LO gluon distribution

D.B. & den Dunnen, NPB 886 (2014) 421

Conclusion: in Higgs production linear gluon polarization contributes at few % level

# Comparison to other results

PHYSICAL REVIEW D **86,** 094026 (2012)

# Improved resummation prediction on Higgs boson production at hadron colliders

Jian Wang,[1] Chong Sheng Li,[1,2,*] Hai Tao Li,[1] Zhao Li,[3,†] and C.-P. Yuan[2,3,‡]

They find permille level effects at the Higgs scale, but using the TMD approach at the LL level yields percent level effects

Wang *et al.* include $\alpha_s^2$ terms, but in denominator only, and also use a different pdf set and $S_{NP}$

$$\tilde{f}_{g/P}(x, b^2; \mu, \zeta) = \sum_{i=g,q} \int_x^1 \frac{d\hat{x}}{\hat{x}} C_{i/g}(x/\hat{x}, b^2; g(\mu), \mu, \zeta) f_{i/P}(\hat{x}; \mu) + \mathcal{O}((\Lambda_{\rm QCD} b)^a)$$

$$\frac{G^{(1)}G^{(1)}\alpha_s^2 + 2G^{(1)}G^{(2)}\alpha_s^3}{C^{(0)}C^{(0)} + 2C^{(0)}C^{(1)}\alpha_s + (C^{(1)}C^{(1)} + 2C^{(0)}C^{(2)})\alpha_s^2} \approx$$

$$\frac{G^{(1)}G^{(1)}\alpha_s^2}{C^{(0)}C^{(0)}} \left(1 + \frac{2G^{(1)}G^{(2)}}{G^{(1)}G^{(1)}}\alpha_s + \mathcal{O}(\alpha_s^2)\right) \left(1 - \frac{2C^{(0)}C^{(1)}}{C^{(0)}C^{(0)}}\alpha_s + \mathcal{O}(\alpha_s^2)\right)$$

They include third factor, but not second
May explain additional suppression partly

# Further resummations

For the TMD at small b one often considers the perturbative tail, which is calculable

$$\tilde{f}_{g/P}(x, b^2; \mu, \zeta) = \sum_{i=g,q} \int_x^1 \frac{d\hat{x}}{\hat{x}} C_{i/g}(x/\hat{x}, b^2; g(\mu), \mu, \zeta) f_{i/P}(\hat{x}; \mu) + \mathcal{O}((\Lambda_{\rm QCD} b)^a)$$

To extend it to be valid at larger b values one can perform further resummation:

$$\tilde{F}^{\rm pert}_{q/N}(x, b_T; \zeta, \mu) = \left(\frac{\zeta b_T^2}{4e^{-2\gamma_E}}\right)^{-D^R(b_T;\mu)} e^{h^R_\Gamma(b_T;\mu) - h^R_\gamma(b_T;\mu)} \sum_j \int_x^1 \frac{dz}{z} \hat{C}_{q\leftarrow j}(x/z, b_T; \mu)\, f_{j/N}(z; \mu)$$

$$\tilde{F}_{q/N}(x, b_T; Q_i^2, \mu_i) = \tilde{F}^{\rm pert}_{q/N}(x, b_T; Q_i^2, \mu_i)\, \tilde{F}^{\rm NP}_{q/N}(x, b_T; Q_i)$$

$$\tilde{F}^{\rm NP}_{q/N}(x, b_T; Q_i) \equiv \tilde{F}^{\rm NP}_{q/N}(x, b_T) \left(\frac{Q_i^2}{Q_0^2}\right)^{-D^{\rm NP}(b_T)}$$

Echevarria, Idilbi, Schäfer, Scimemi, EPJC 73 (2013) 2636

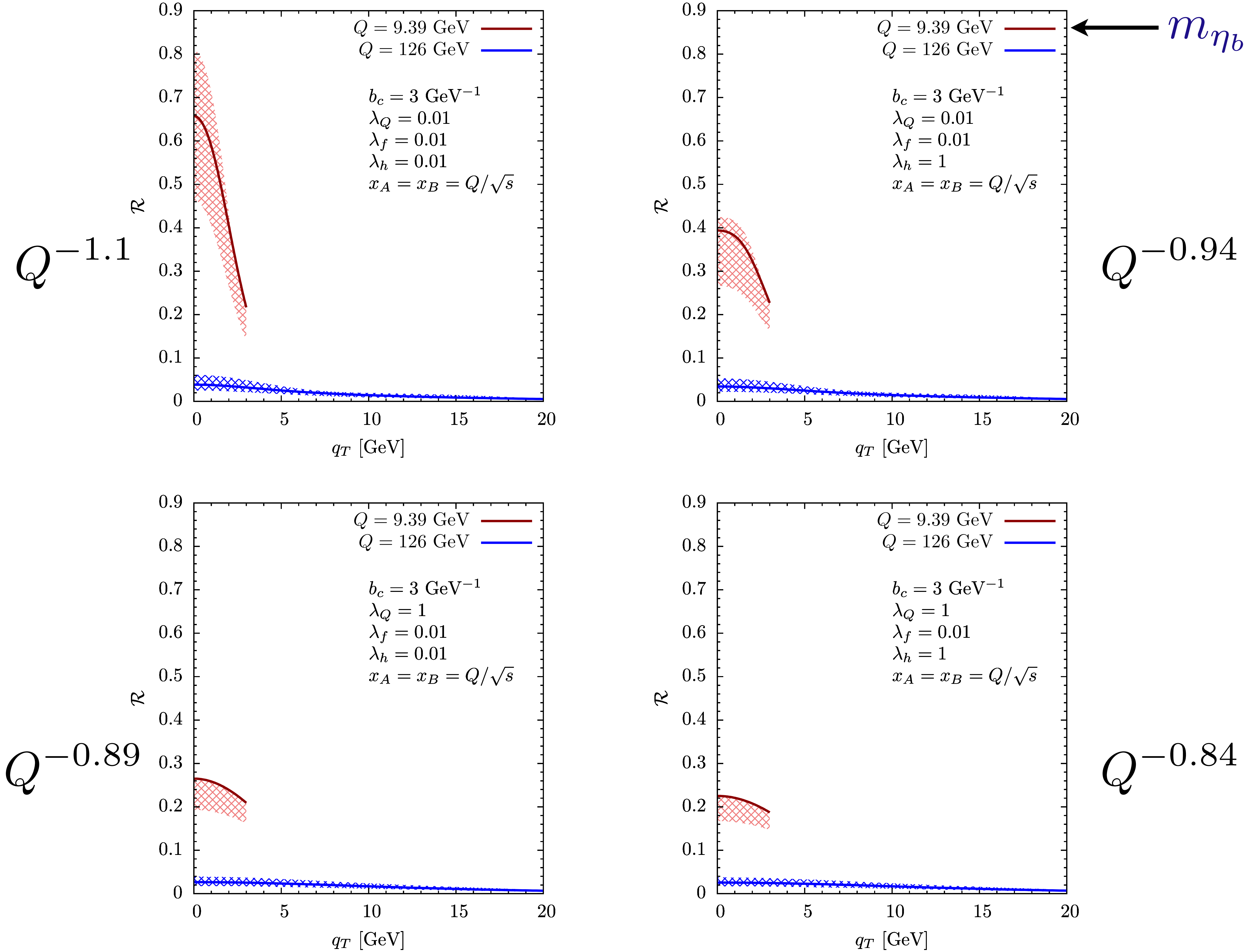
D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (2014) 098

$$\tilde{F}^{f,NP}_{j/A}(x_A, b_T; Q) = \exp\left[-b_T^2(\lambda_f + \lambda_Q \ln(Q^2/Q_0^2))\right], \qquad Q_0 = 1\ \text{GeV}$$

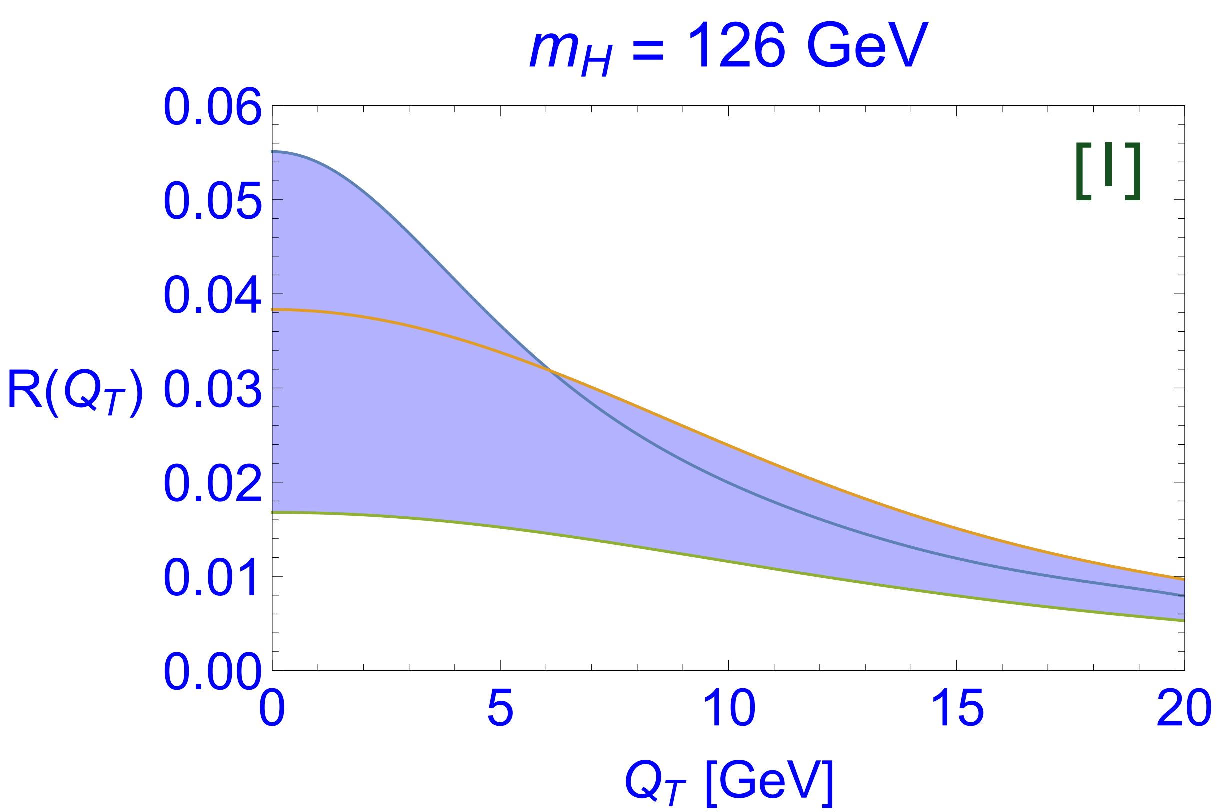
$$\tilde{F}^{h,NP}_{j/A}(x_A, b_T; Q) = \exp\left[-b_T^2(\lambda_h + \lambda_Q \ln(Q^2/Q_0^2))\right], \qquad Q_0 = 1\ \text{GeV}$$

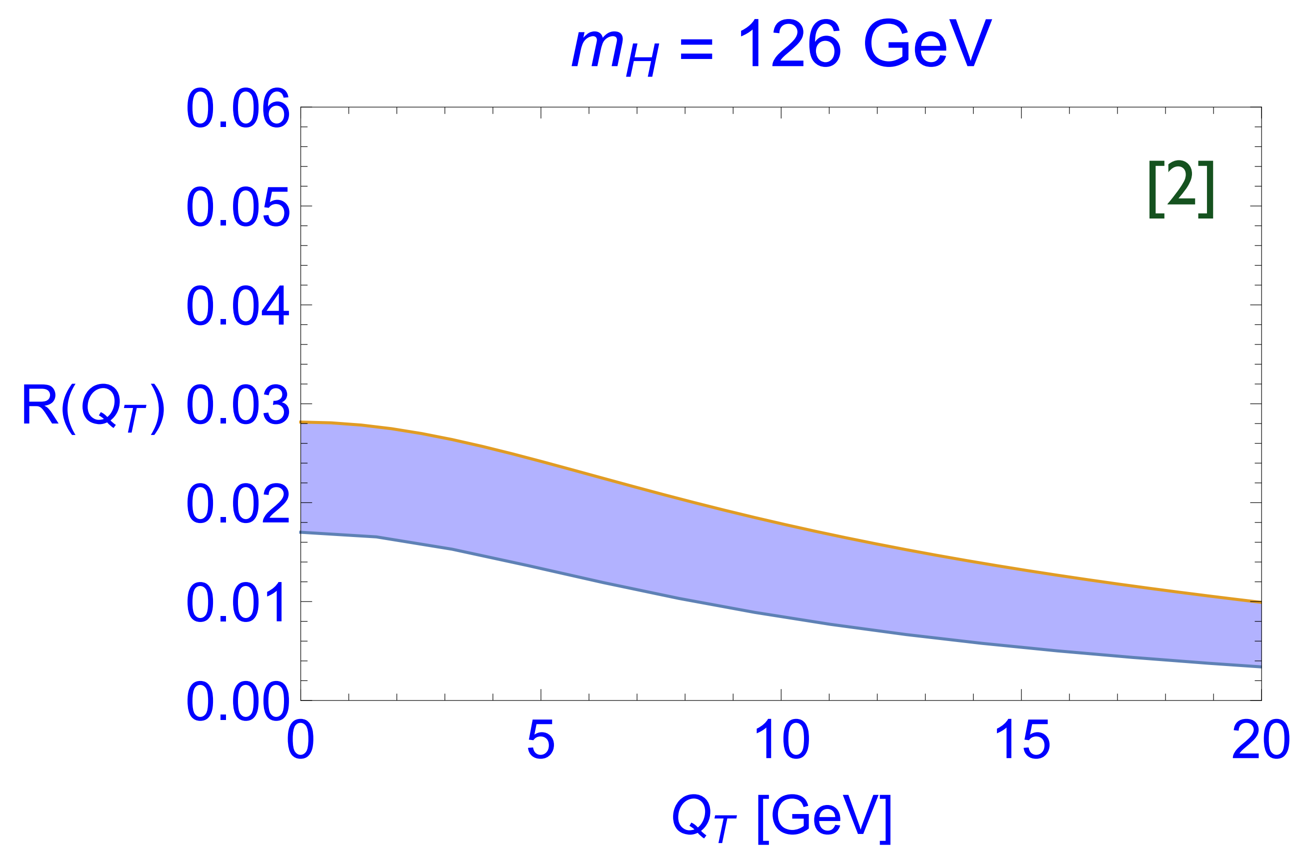
$h_1^{\perp g}$ in $p\,p \to H\ X$

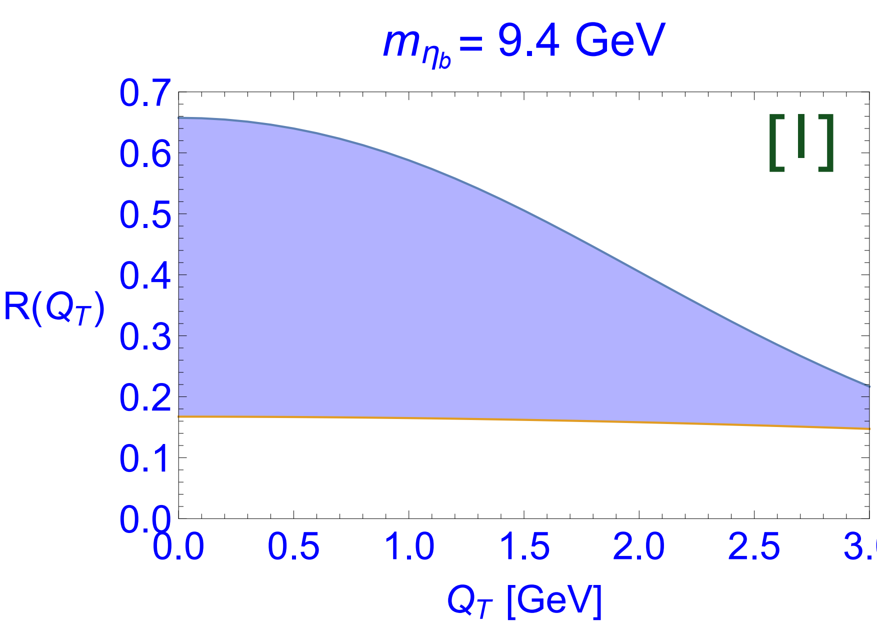
Echevarria, Kasemets, Mulders, Pisano, arXiv:1502.05354

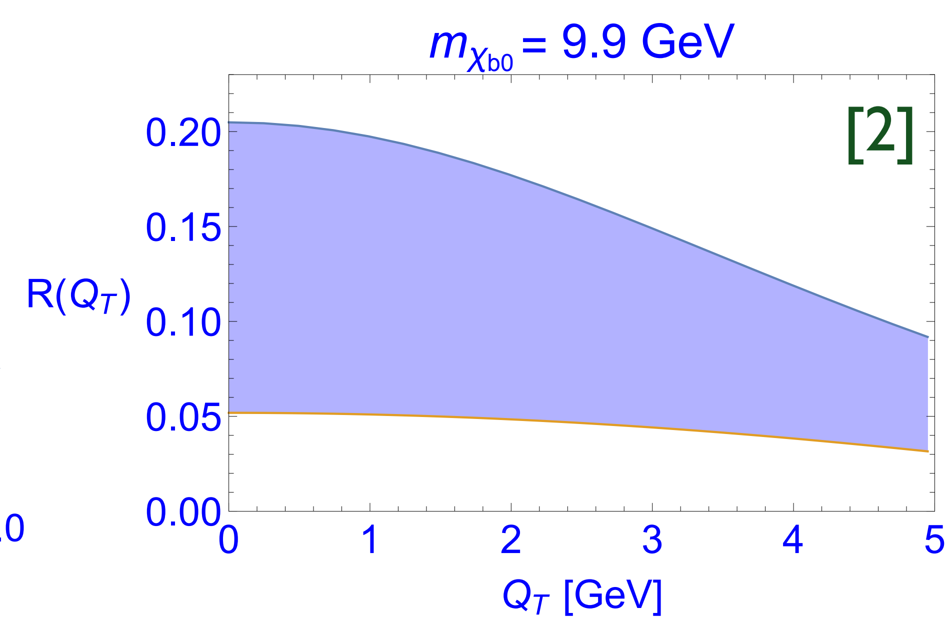


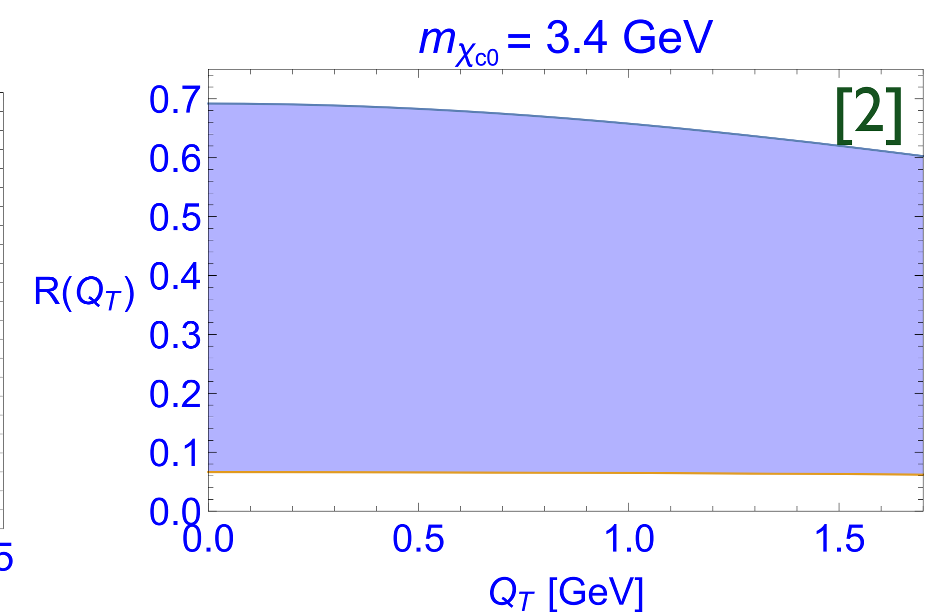
# Range of predictions





[1] Echevarria, Kasemets, Mulders, Pisano, arXiv:1502.05354

[2] D.B. & den Dunnen, NPB 886 (2014) 421

# Uncertainties

# Intermediate b values

In the TMD factorized expression there may be nonperturbative contributions from small $p_T$ which mainly affect large b

The perturbative tail holds for small b which is dominated by large $p_T$, but there is an intermediate region

To study the significance of this region, we consider a model which is approximately Gaussian at low $p_T$ and has the correct tail at high $p_T$ or small b:

$$f_1^g(x, p_T^2) = f_1^g(x) \frac{R^2}{2\pi} \frac{1}{1 + p_T^2 R^2} \qquad R = 2\,\mathrm{GeV}^{-1}$$

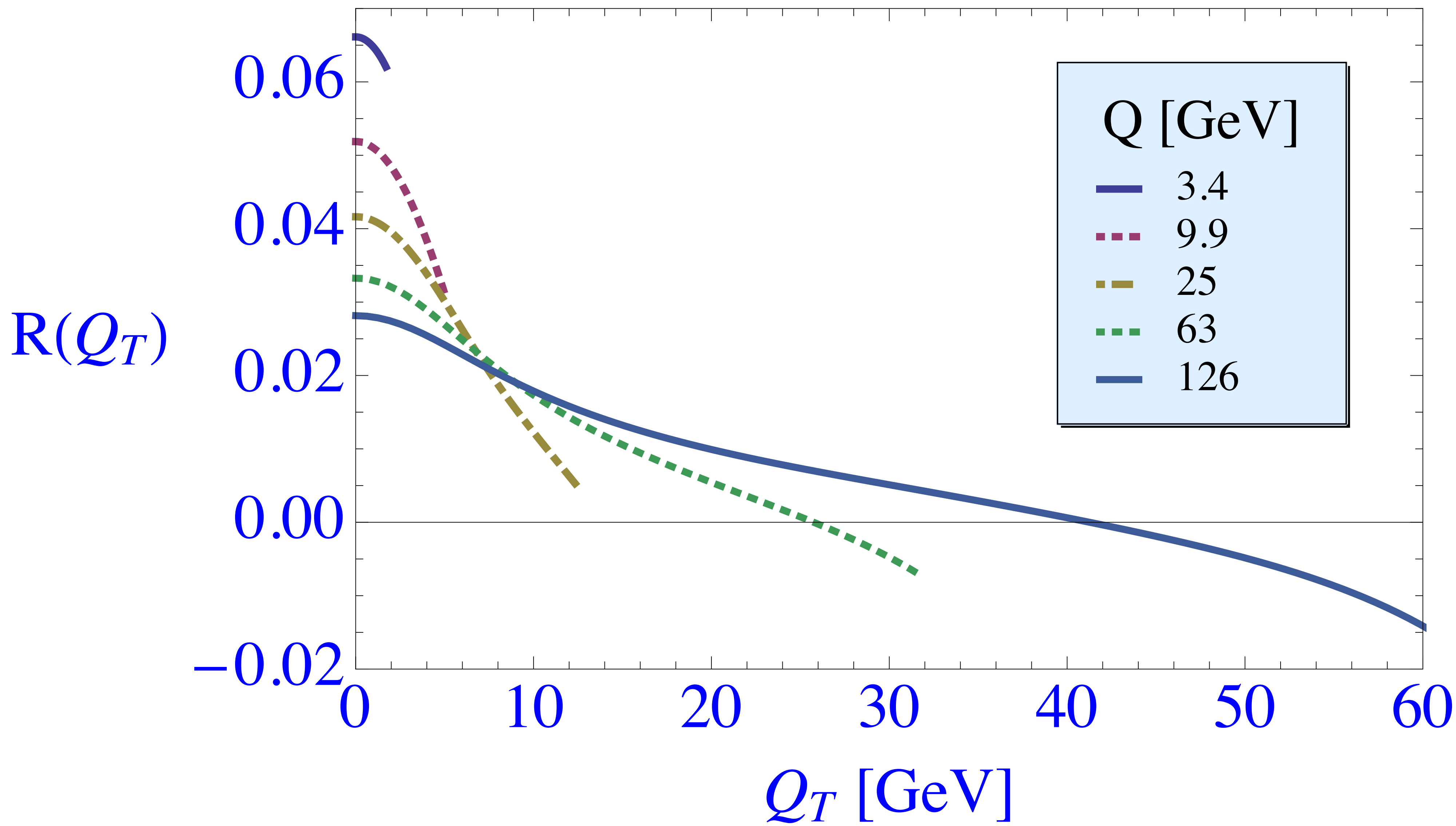
$$h_1^{\perp g}(x, p_T^2) = c f_1^g(x) \frac{M^2 R_h^4}{2\pi} \frac{1}{(1 + p_T^2 R_h^2)^2}$$

To satisfy Soffer-like bound: $R_h^2 = 3R^2/2 \qquad c = 2$

# Gaussian+tail model

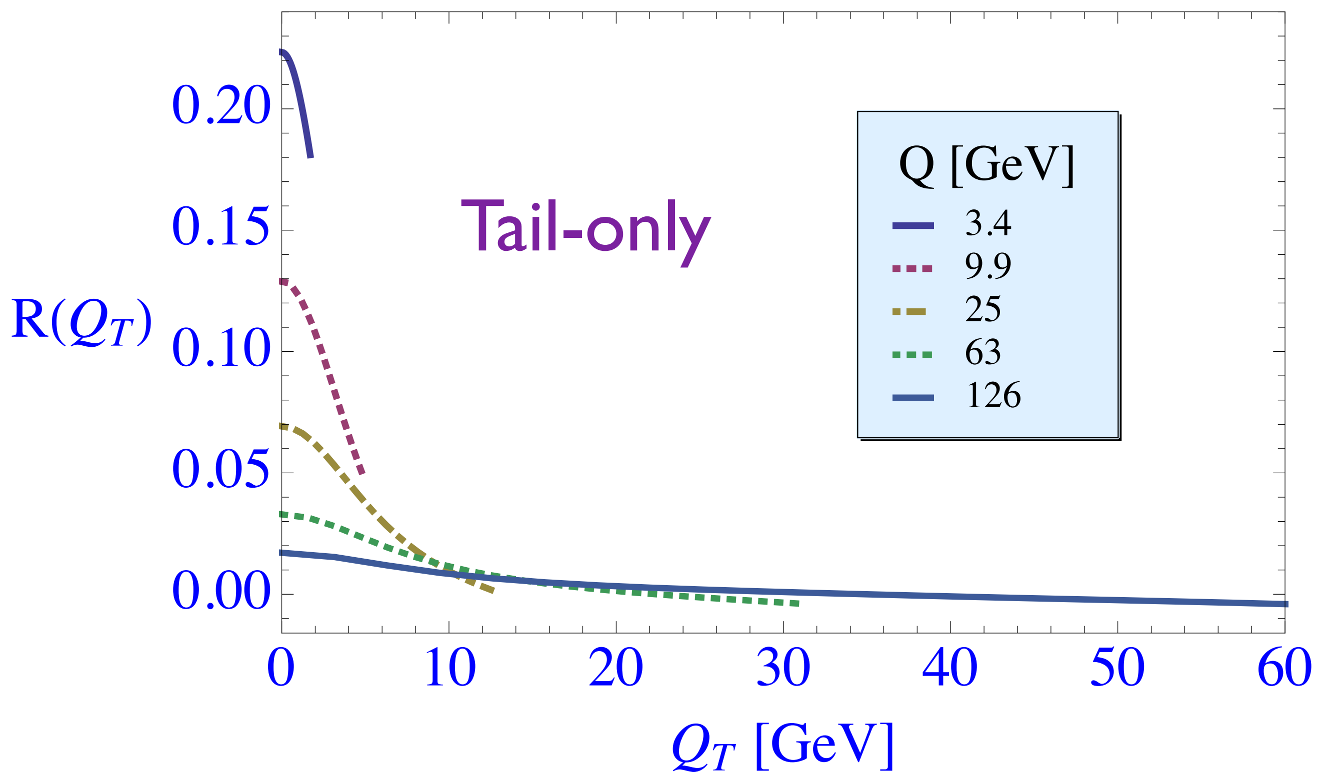
$$\tilde{f}_1^g(x, b^2; \mu_b^2, \mu_b) = f_1^g(x; \mu_b) K_0(b/R) / \ln(R b_0/b + 1)$$

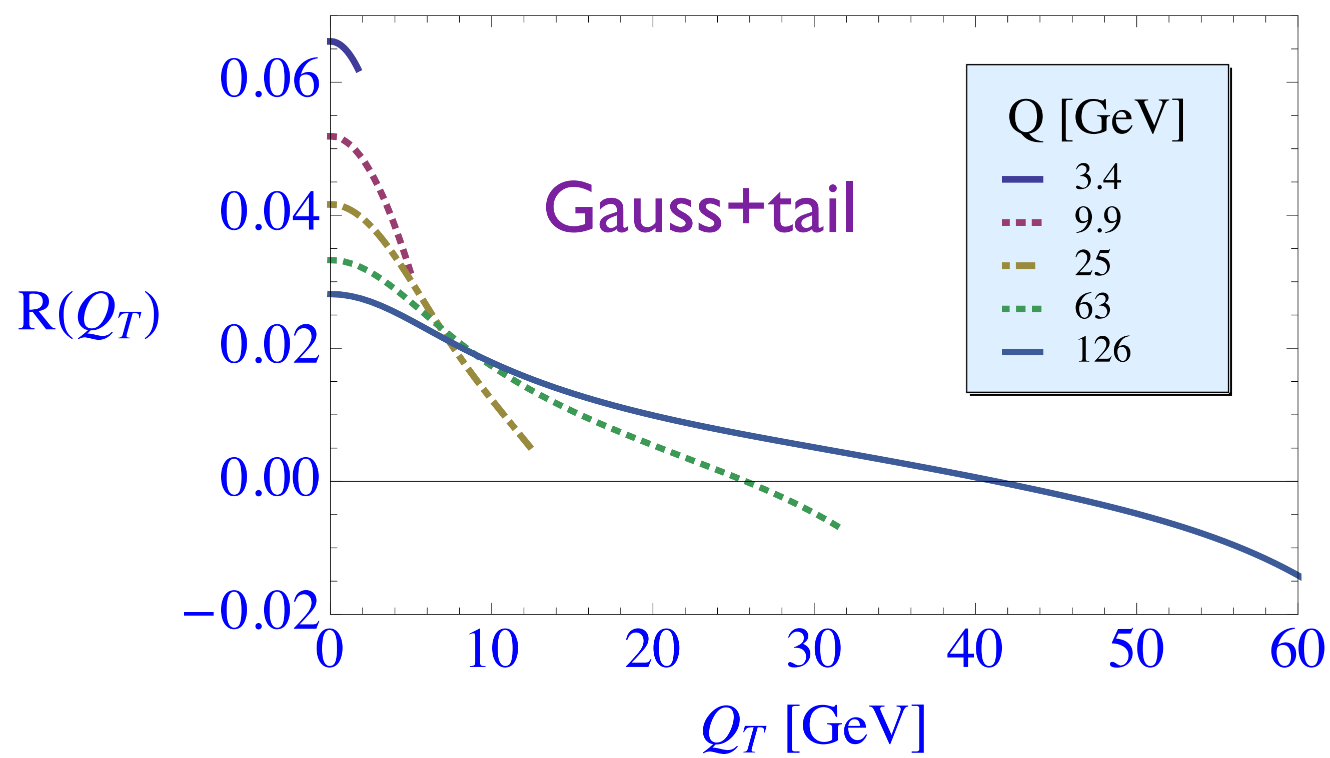
$$\tilde{h}_1^{\perp g}(x, b^2; \mu_b^2, \mu_b) = \frac{c}{4} f_1^g(x; \mu_b) \frac{b}{R_h} K_1(b/R_h) / \ln(R_h b_0/b + 1)$$

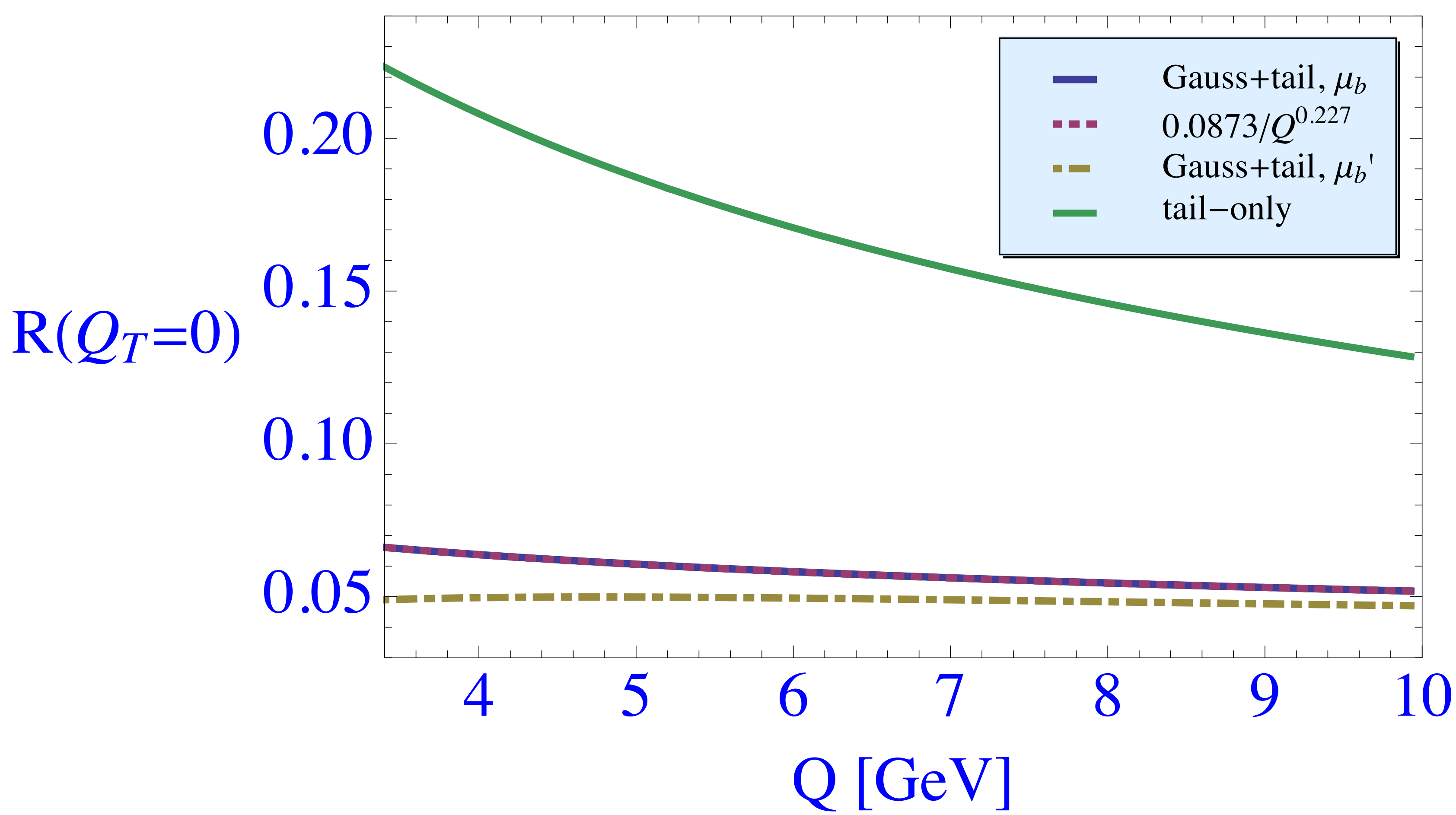



Gaussian+tail yields much smaller contributions at small Q

# Comparison




Gaussian+tail evolves much more slowly than tail-only expression

# Very small b region

For very small b region (b << 1/Q) the perturbative expressions for $S_A$ flip sign

$$S_A(b,Q) = \frac{C_A}{\pi}\int_{\mu_b^2}^{Q^2}\frac{d\mu^2}{\mu^2}\alpha_s(\mu)\,[\ldots] \overset{b\ll 1/Q}{\longrightarrow} -\frac{C_A}{\pi}\int_{Q^2}^{\mu_b^2}\frac{d\mu^2}{\mu^2}\alpha_s(\mu)\,[\ldots]$$

As a consequence σ ~ F.T. [W(b)] < 0 at larger $q_T$

See e.g. Boglione, Gonzalez Hernandez, Melis, Prokudin, 1412.1383

Well-known problem. Use standard regularization:

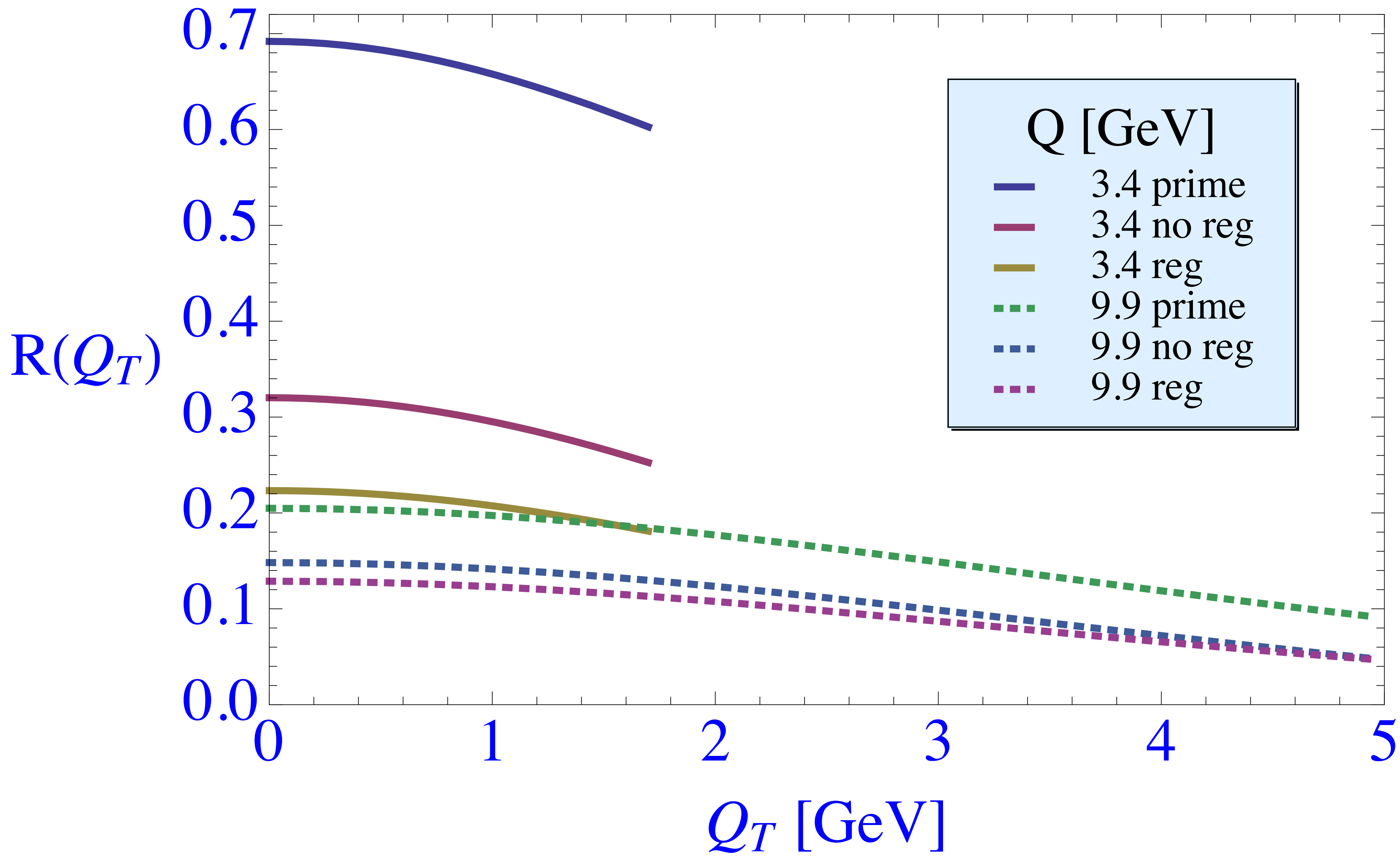
$$Q^2/\mu_b^2 = b^2Q^2/b_0^2 \to Q^2/{\mu_b'}^2 \equiv (bQ/b_0+1)^2$$

Parisi, Petronzio, 1985

Precise form of Parisi-Petronzio regularization usually irrelevant since matching to Y-term is needed anyway, *but not so in the Higgs case where the problem already arises at $q_T$=0*!

# Very small b region

At low Q there is quite some uncertainty from the very small b region (b << 1/Q)



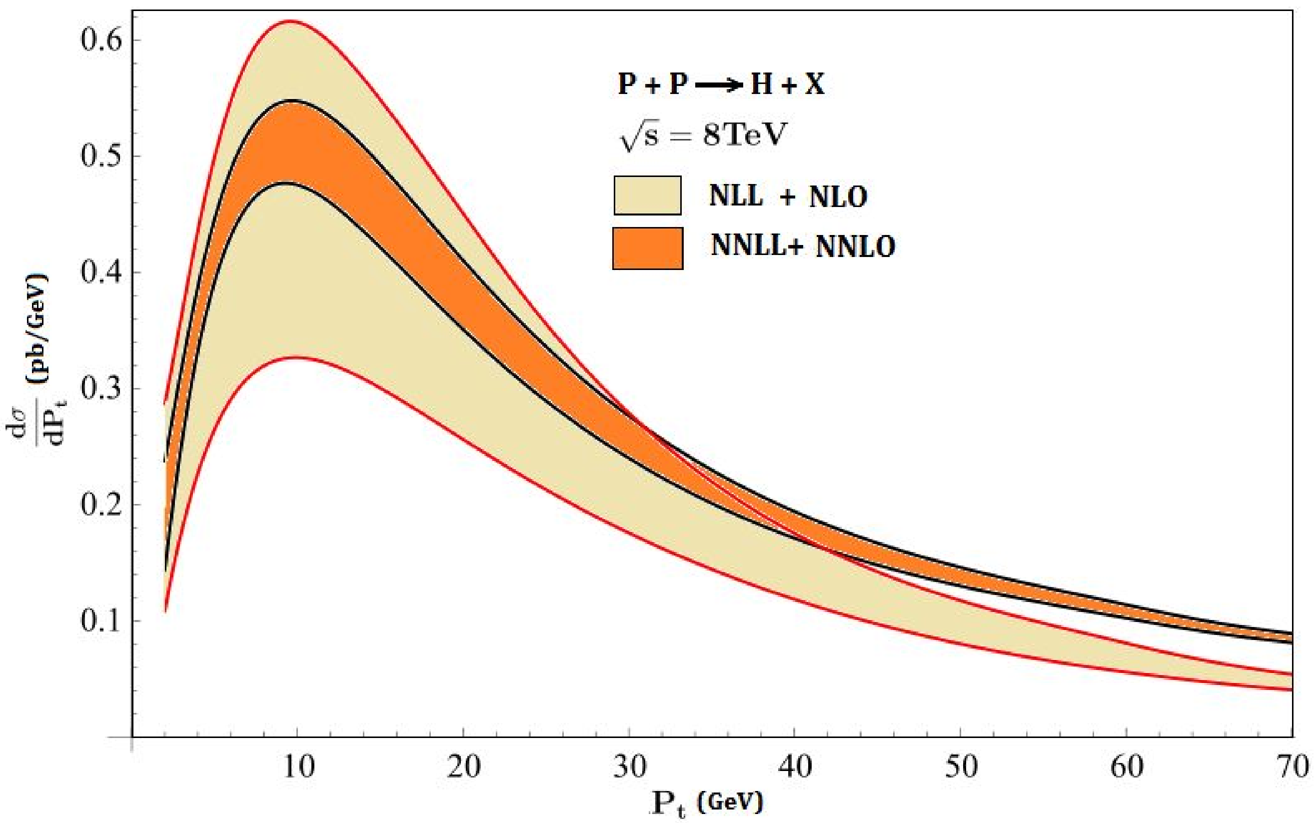

reg=standard regularization:

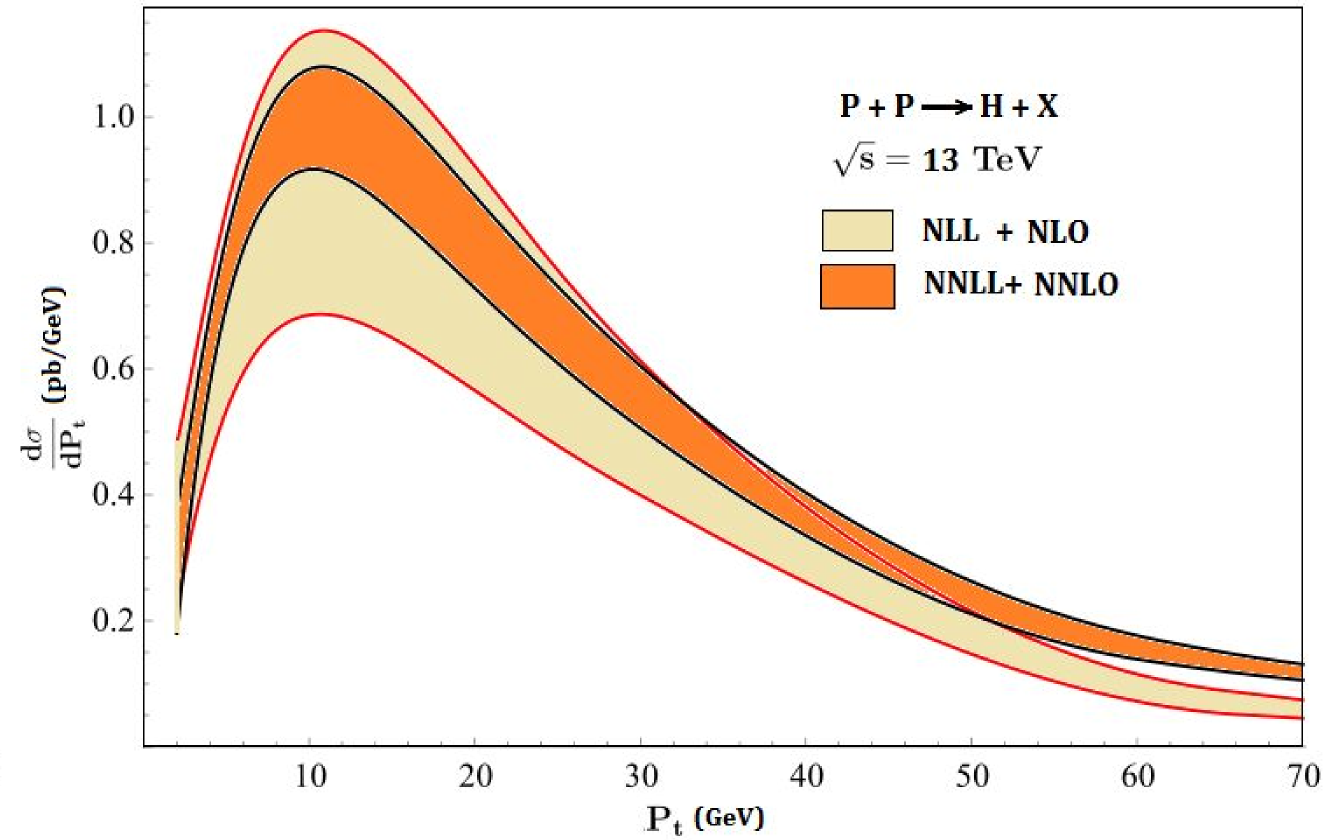
$$Q^2/\mu_b^2 = b^2 Q^2/b_0^2 \rightarrow Q^2/{\mu_b'}^2 \equiv (bQ/b_0 + 1)^2$$

Parisi, Petronzio, 1985

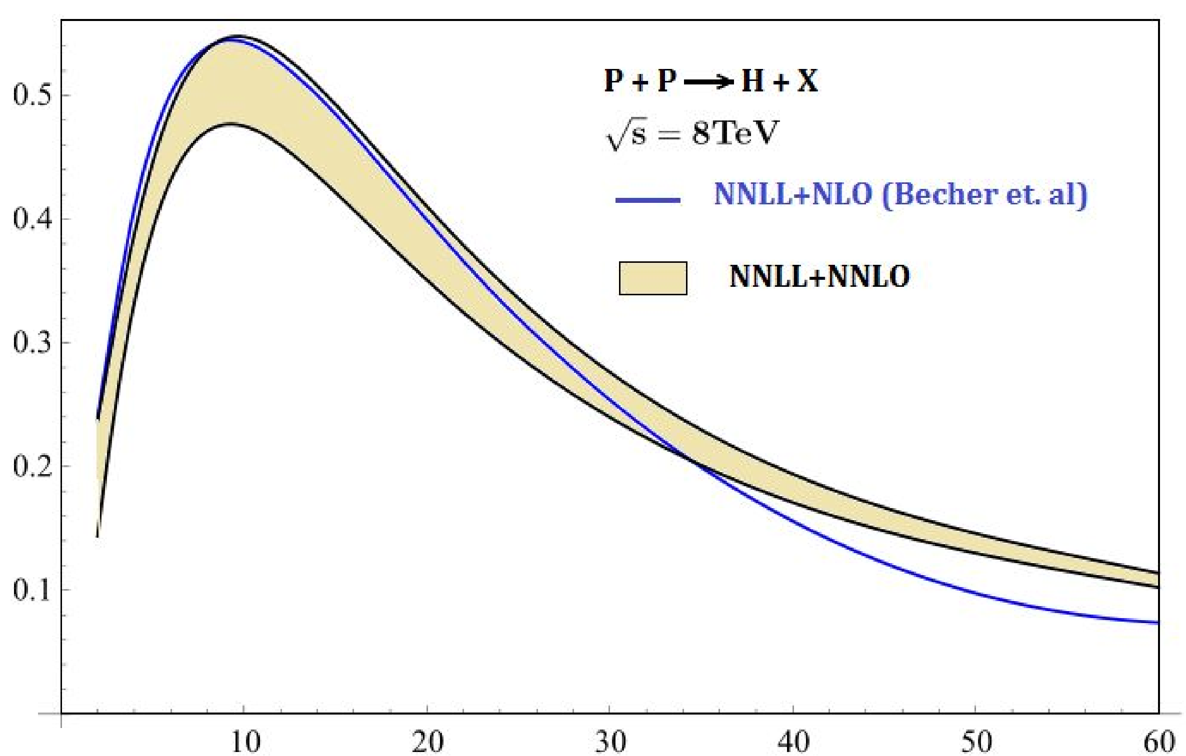
prime=evolve everything to scale $\mu_b$'

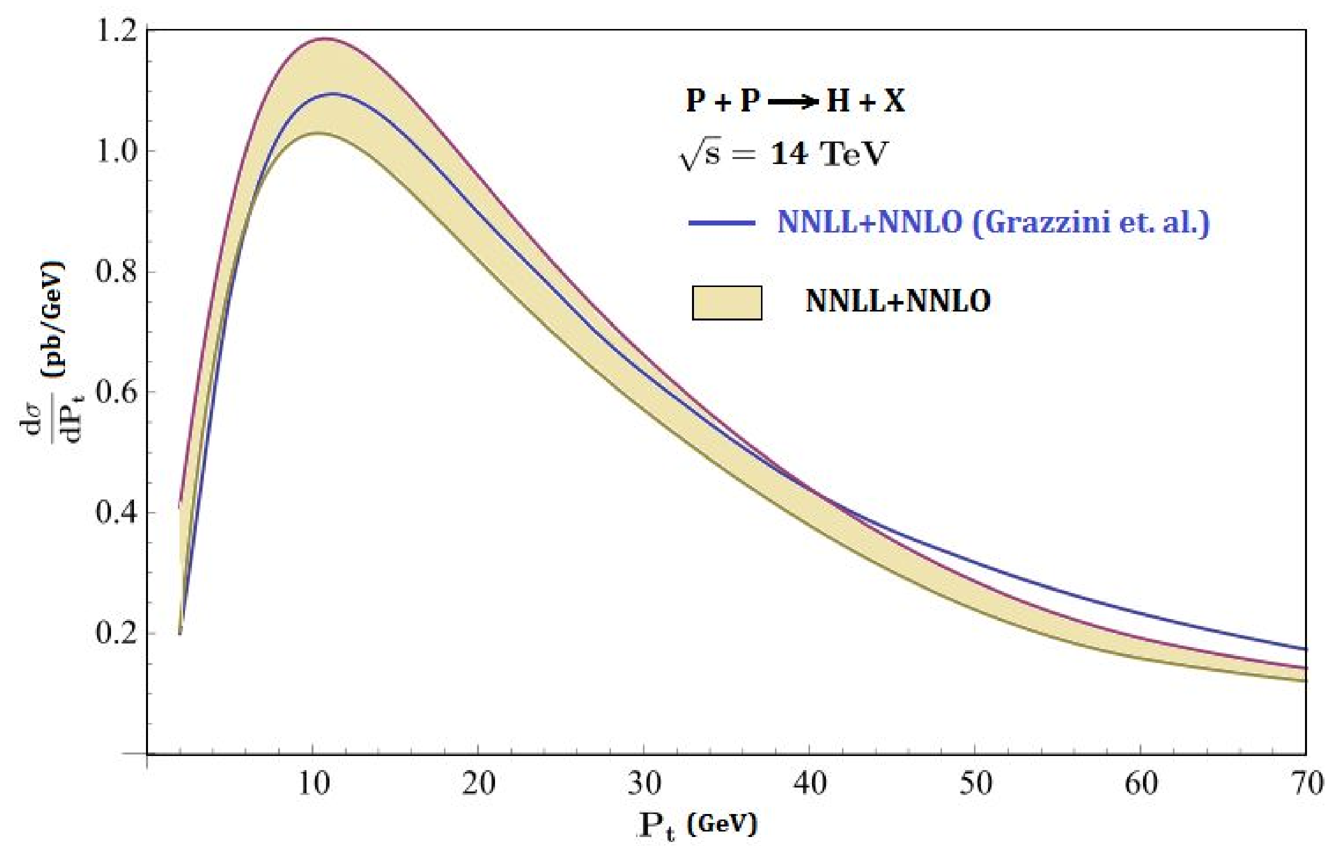
# Feasibility



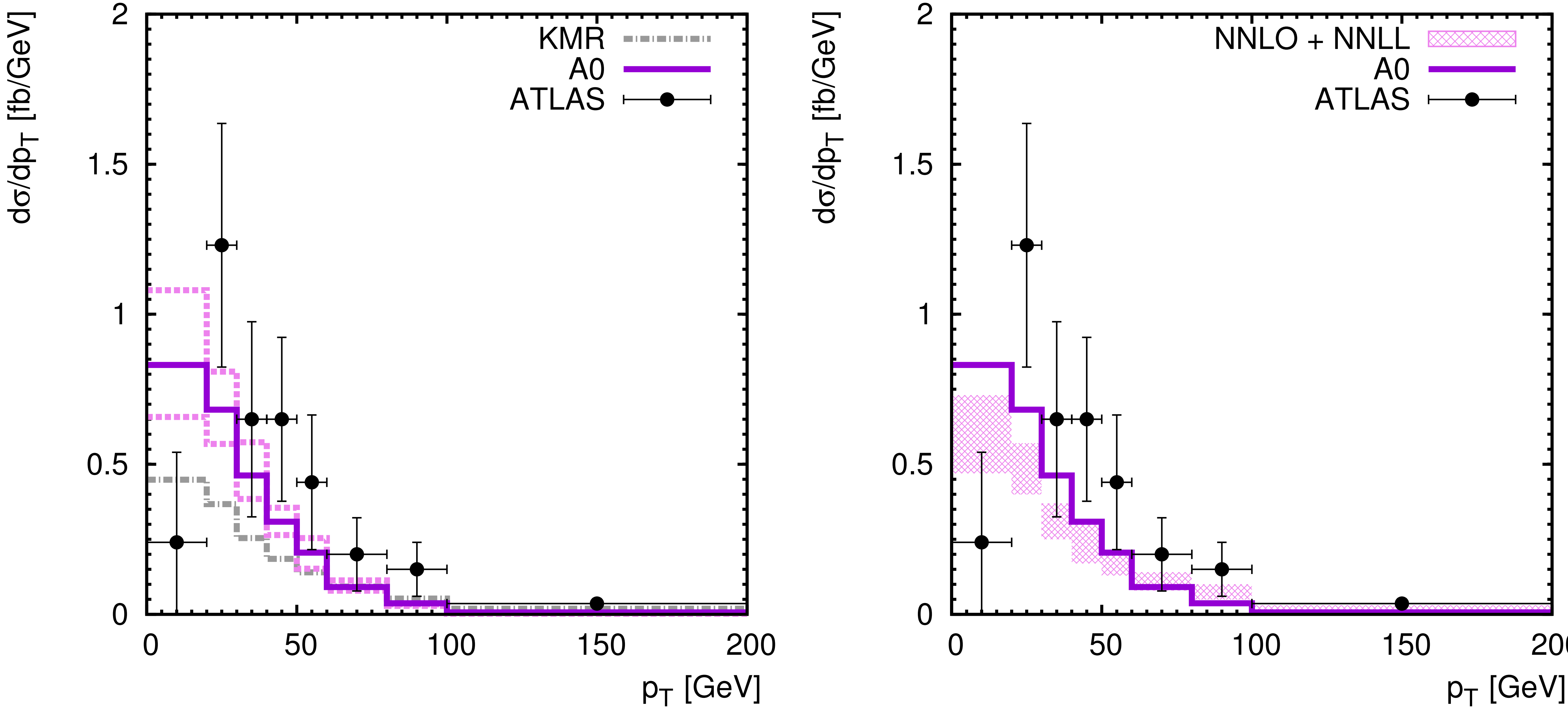

Neill, Rothstein, Vaidya, arXiv:1503.00005




NNLL+NNLO has 10-20% uncertainty, plus an unknown nonperturbative contribution

# $p_T$ resolution




A.V. Lipatov, M.A. Malyshev, N.P. Zotov, PLB 735, 79 (2014)

Data from ATLAS-CONF-2013-072

Current pT resolution of Higgs too low at low pT, will eventually be around 5 GeV

Study of the heavy quarkonia is probably more promising, perhaps less challenging, but theoretical uncertainties are significantly larger

# Higgs decay channels

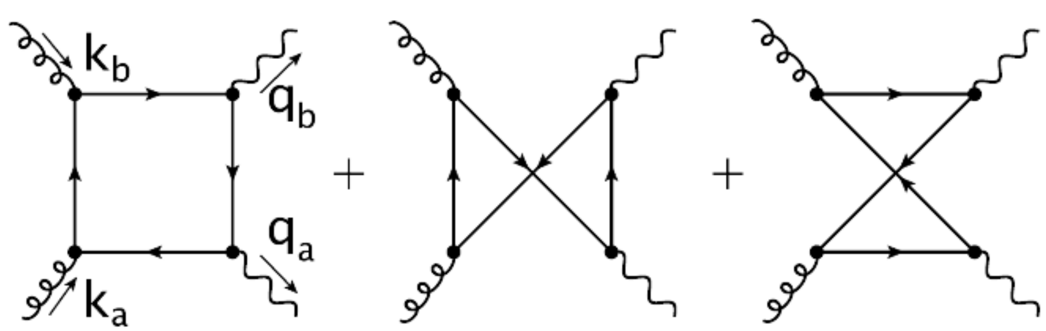
In reality the Higgs boson decays

Energy resolution becomes important
$\Delta Q$=0.5 GeV in $\gamma\gamma$ channel

There will be background processes to deal with

Linearly polarized gluons also enter in the process gg → $\gamma\gamma$ without Higgs

[Nadolsky, Balazs, Berger, Yuan, '07; ,Qiu, Schlegel, Vogelsang '11]




Percent level $R(Q_T)$ from gg → $\gamma\gamma$ at RHIC energy
Qiu, Schlegel, Vogelsang, PRL '11

At small $p_T$ gg → $\gamma\gamma$g dominates
Szczurek, Luszczak, Maciula, PRD 90, 094023 (2014)

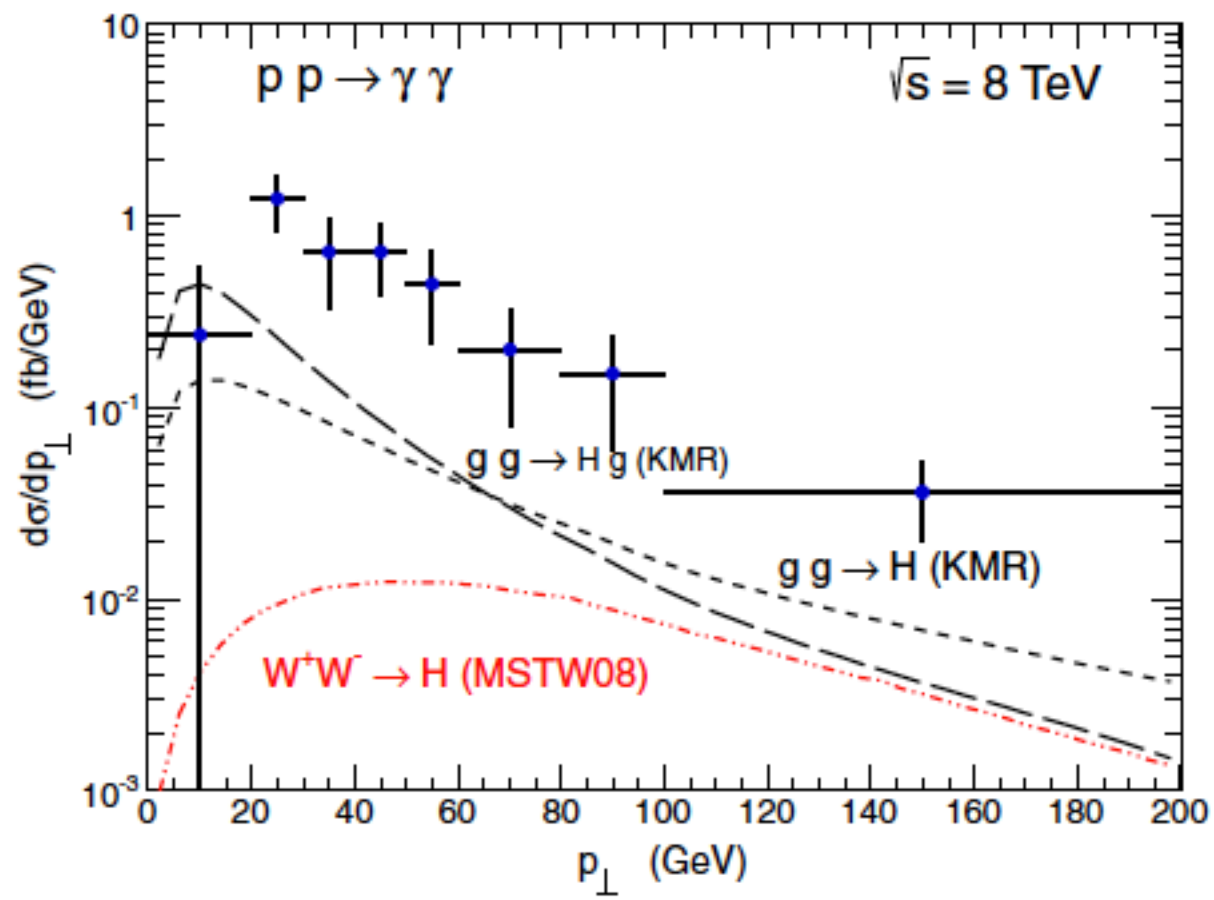
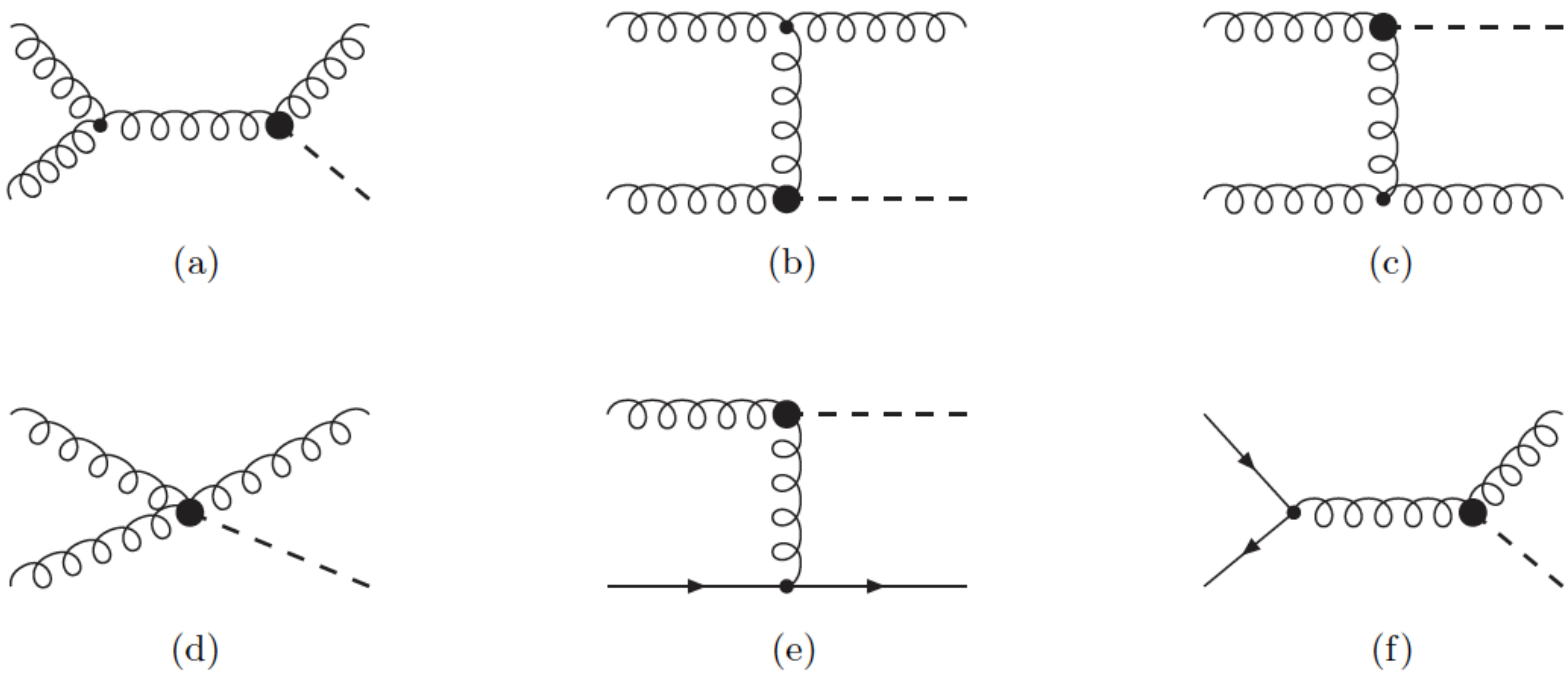
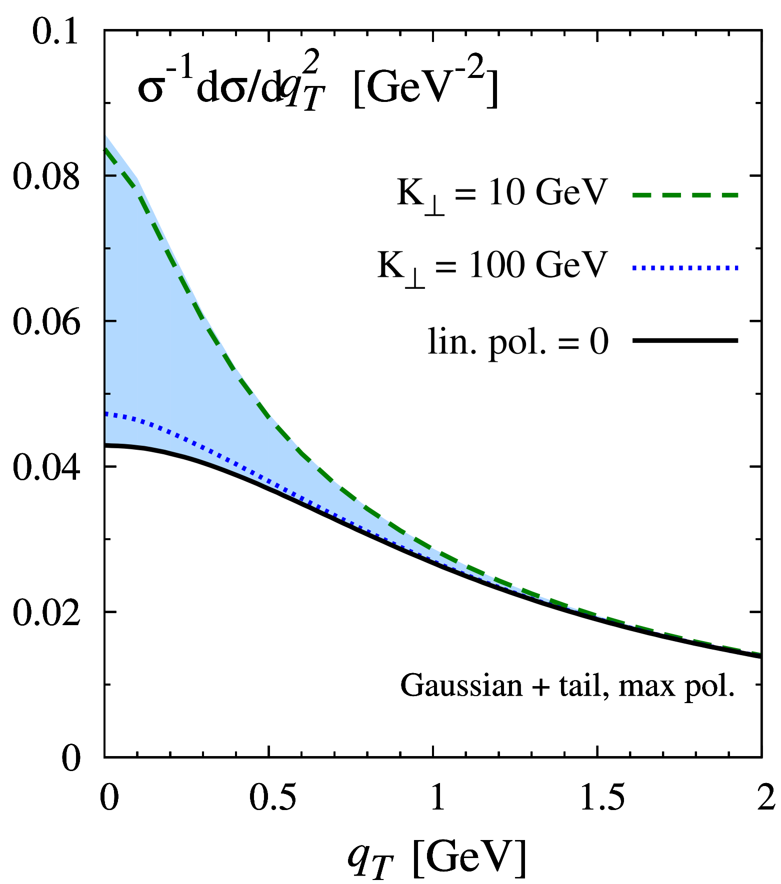
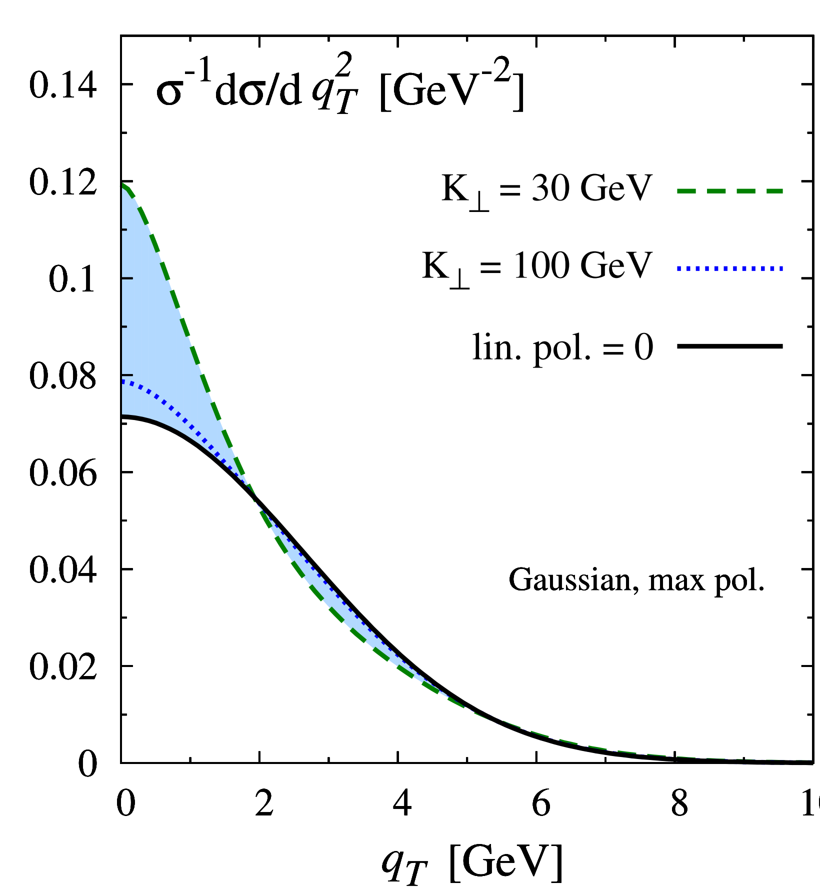



FIG. 26 (color online). Transverse momentum distribution of the Higgs boson in the $\gamma\gamma$ channels for different mechanisms: $gg \to H$ (solid line), $gg \to Hg$ (dashed line) and $WW \to H$ (dash-dotted line).

# Higgs+jet production



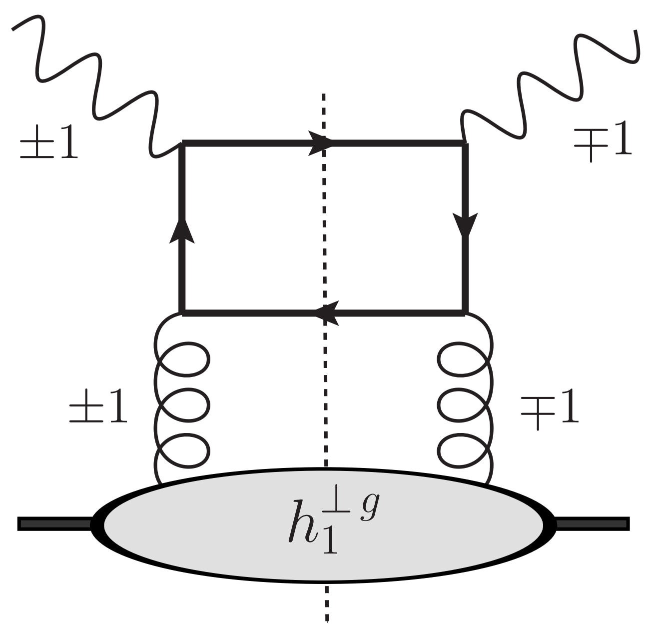

[D.B., Pisano, arXiv:1412.5556]

# Electron-ion collisions

# Heavy quark production

$h_1^{\perp g}$ can be probed in charm and bottom quark production
Here it appears only once, so less suppressed

$$ep \to e' Q\bar{Q}X$$




It leads to a cos $2(\phi_T$-$\phi_\perp)$ asymmetry in heavy quark pair production in DIS
$\phi_{T/\perp}$: angles of $K_\perp^Q \pm K_\perp^{\bar{Q}}$

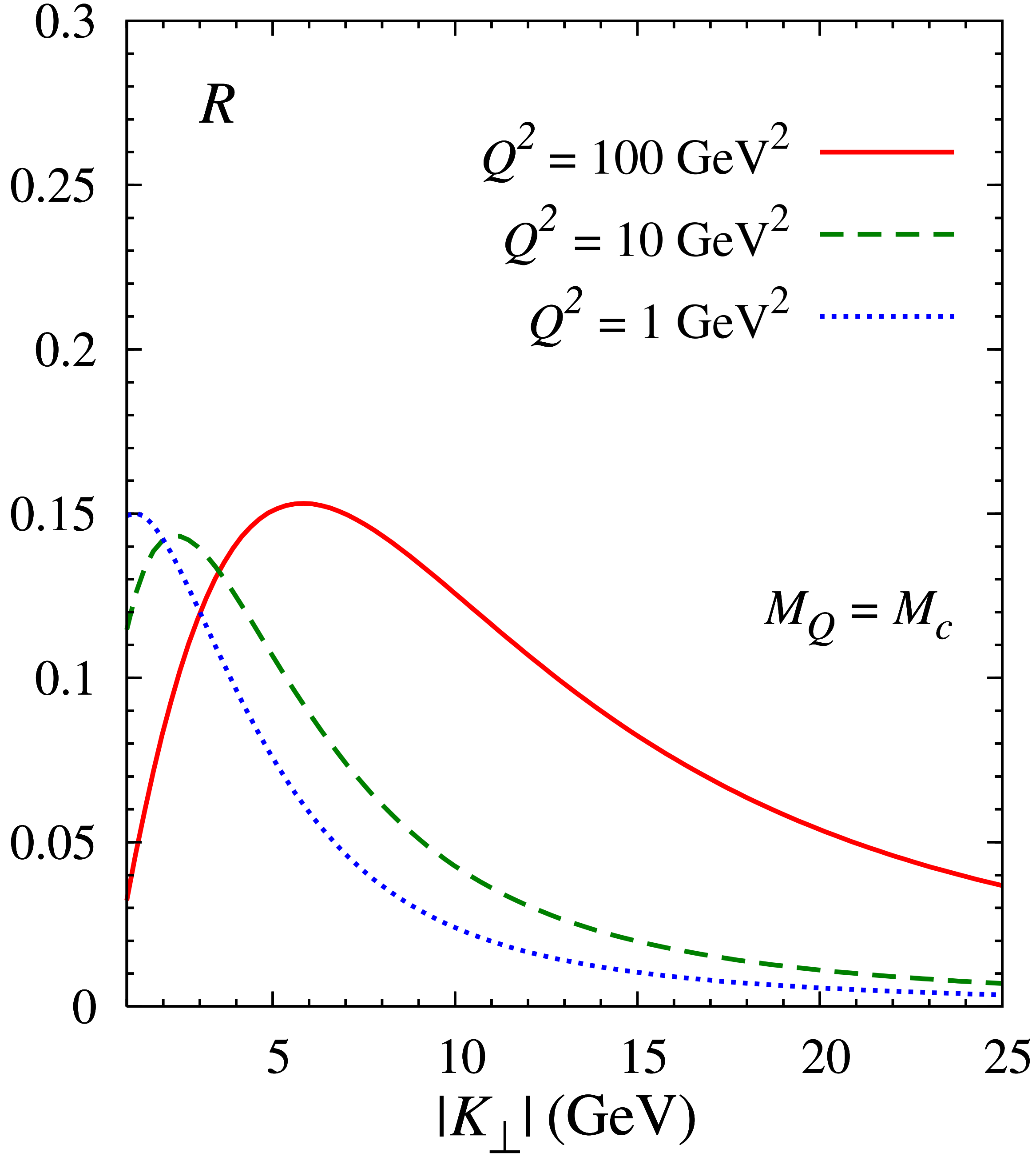
[D.B., Brodsky, Mulders & Pisano, '10]

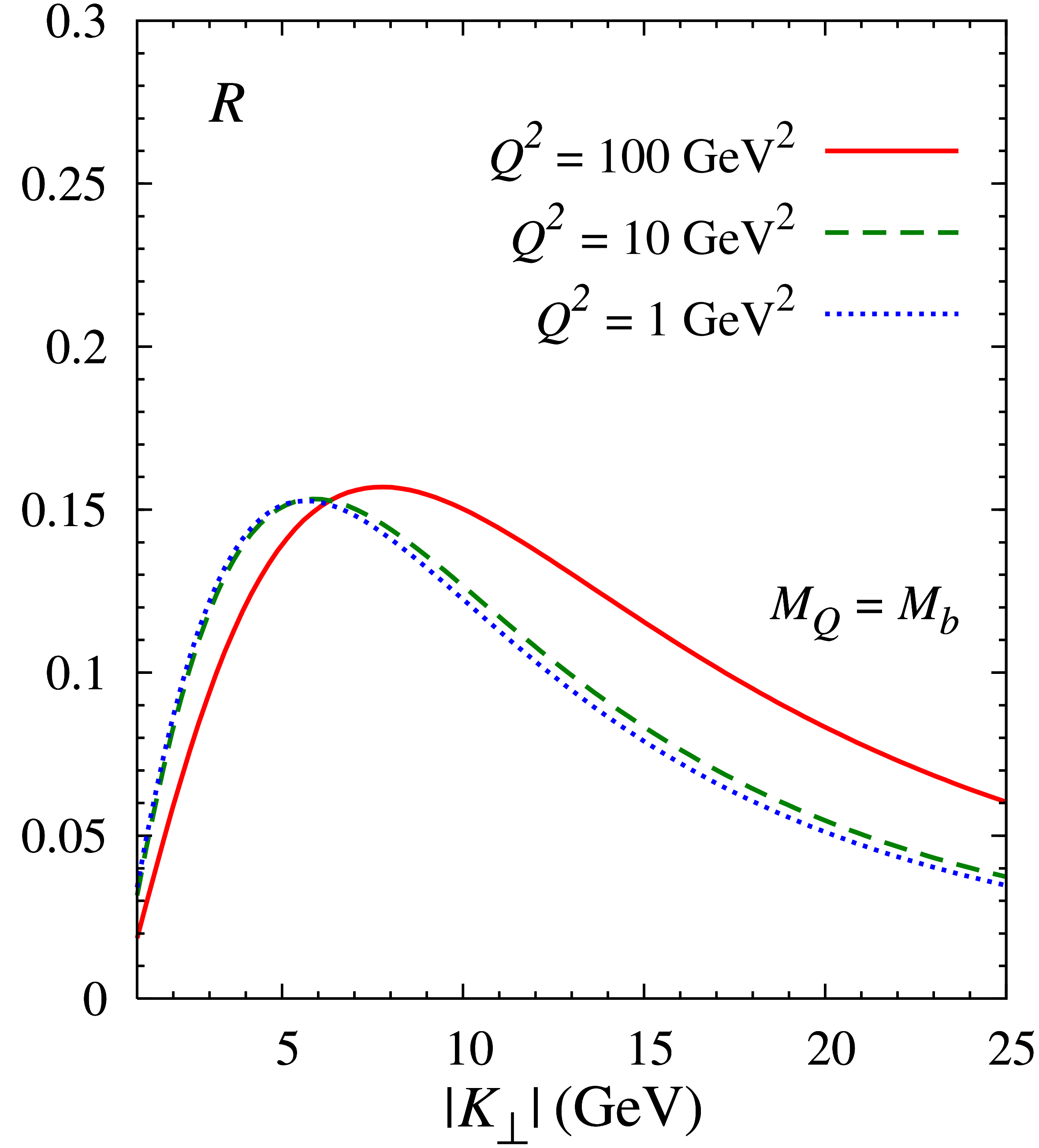
Best measured at an Electron-Ion Collider (USA) or LHeC (CERN)

EIC is best for this, because of problems with factorization in pp (RHIC, LHC)
Rogers, Mulders '10

# Maximum asymmetries in heavy quark production

$ep \to e'Q\bar{Q}X$ $\qquad$ $R = \text{bound on } |\langle \cos 2(\phi_T - \phi_\perp)\rangle|$

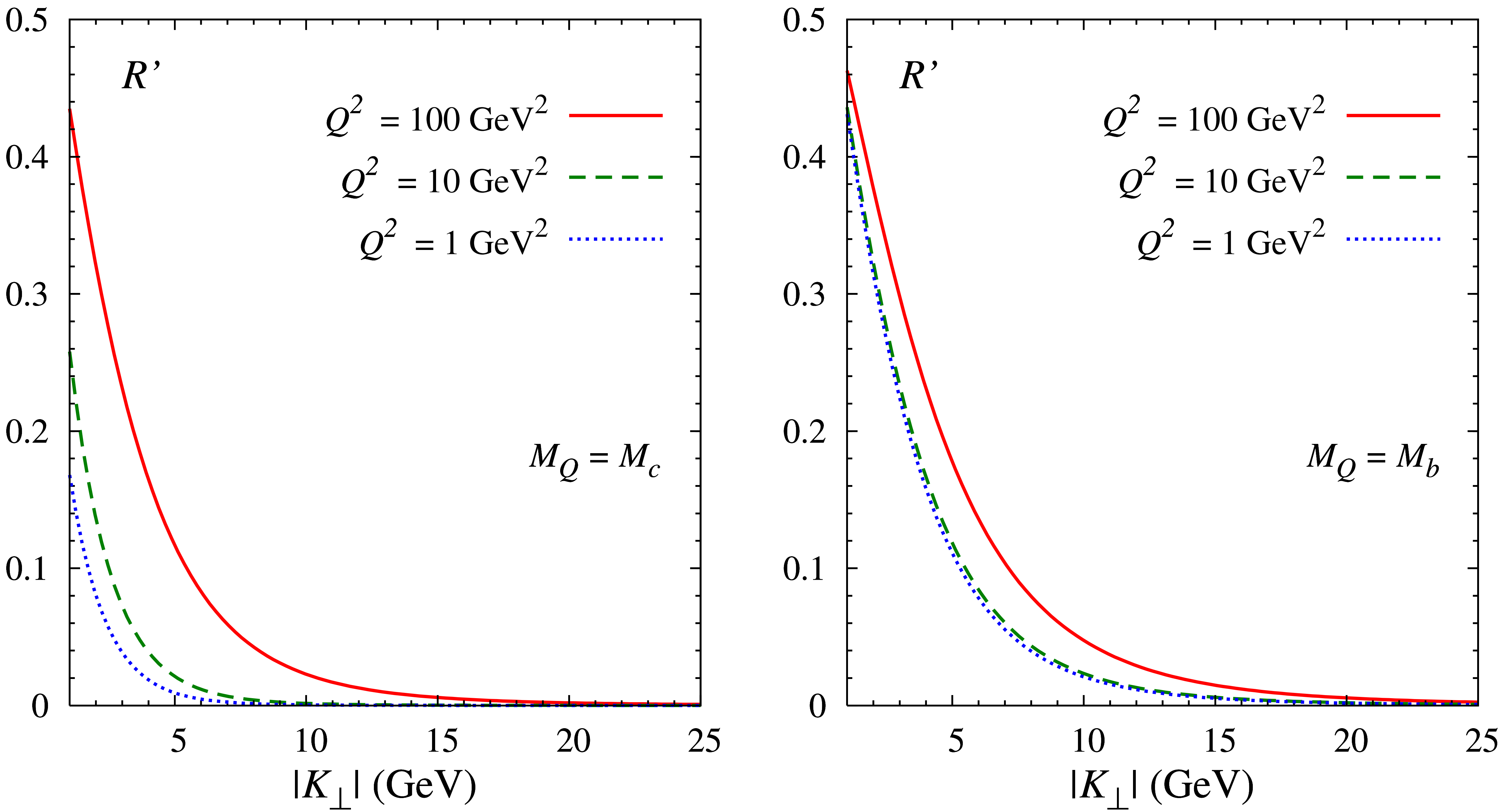



Pisano, D.B., Brodsky, Buffing & Mulders, JHEP 10 (2013) 024

# Maximum asymmetries in heavy quark production

$ep \to e' Q\bar{Q} X$ $\qquad$ $R' = \text{bound on } |\langle \cos 2(\phi_\ell - \phi_T) \rangle|$




Pisano, D.B., Brodsky, Buffing & Mulders, JHEP 10 (2013) 024

# Small x

# Gluon polarization at small x

Does the linear gluon polarization matter at small-x?
*Circular* polarization $\Delta g(x)$ is suppressed w.r.t. g(x) at small x

Its evolution kernel does not have 1/x behavior:

$$\Delta P_{gg}(z) = \frac{2C_A(2-z)}{1-z}$$

Linearly polarized gluon distribution inside unpolarized protons does grow with 1/x:

$$\tilde{h}_1^{\perp g}(x, b^2; \mu_b^2, \mu_b) = \frac{\alpha_s(\mu_b) C_A}{2\pi} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left( \frac{\hat{x}}{x} - 1 \right) f_{g/P}(\hat{x}; \mu_b) + \mathcal{O}(\alpha_s^2)$$

It turns out the linear polarization can even become maximal!

# Linear gluon polarization at small x

At small x the WW (or CGC) gluon field and the dipole distribution have been studied:

$$h_{1,WW}^{\perp g} \ll f_{1,WW}^{\perp g} \quad \text{for } k_\perp \ll Q_s, \qquad h_{1,WW}^{\perp g} = 2 f_{1,WW}^{\perp g} \quad \text{for } k_\perp \gg Q_s$$

$$x h_{1,DP}^{\perp g}(x, k_\perp) = 2x f_{1,DP}^{g}(x, k_\perp)$$

Metz, Zhou '11

At small x the "$k_T$-factorization" approach (CCFM) yields maximum polarization too:

$$\Phi_g^{\mu\nu}(x, \boldsymbol{p}_T)_{\text{max pol}} = \frac{2}{x} \frac{p_T^\mu p_T^\nu}{\boldsymbol{p}_T^2} f_1^g$$

Catani, Ciafaloni, Hautmann, 1991

Applied to Higgs production by Lipatov, Malyshev, Zotov, PLB 735 (2014) 79

There is no theoretical reason why it should be small, especially at small x

But note that what matters is the b space expression, i.o.w. the full $k_T$ range

# Small x

At small-x there are two unpolarized "universal" gluon distributions

Dominguez, Marquet, Xiao, Yuan, 2011

$$xG^{(1)}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \langle P|\mathrm{Tr}\left[F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[+]\dagger}F^{+i}(0)\mathcal{U}^{[+]}\right]|P\rangle$$

$$xG^{(2)}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \langle P|\mathrm{Tr}\left[F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[-]\dagger}F^{+i}(0)\mathcal{U}^{[+]}\right]|P\rangle$$

Recall "A tale of two gluon distributions", Kharzeev, Kovchegov, Tuchin, PRD 68 (2003) 094013

Involvement of the two "universal" gluon distributions in various processes:

| | DIS and DY | SIDIS | hadron in $pA$ | photon-jet in $pA$ | Dijet in DIS | Dijet in $pA$ |
|---|---|---|---|---|---|---|
| $G^{(1)}$ (WW) | $\times$ | $\times$ | $\times$ | $\times$ | $\surd$ | $\surd$ |
| $G^{(2)}$ (dipole) | $\surd$ | $\surd$ | $\surd$ | $\surd$ | $\times$ | $\surd$ |

Dominguez *et al.*:"The large $N_c$ limit is essential in order to eliminate other non-universal distributions or correlators in other different dijet channels, i.e., $qg \to qg$ , $gg \to q\bar{q}$ and $gg \to gg$ in pA collisions"

# Gluon polarization at small x

| | DIS and DY | SIDIS | hadron in $pA$ | photon-jet in $pA$ | Dijet in DIS | Dijet in $pA$ |
|---|---|---|---|---|---|---|
| $h_1^\perp$ (WW) | $\times$ | $\times$ | $\times$ | $\times$ | $\surd$ | $\surd$ |
| $h_1^\perp$ (dipole) | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\surd$ |

DIS, DY, SIDIS, hadron and $\gamma$+jet in pA are in leading power not sensitive to $h_1^{\perp g}$

D.B., Mulders, Pisano, PLB 660 (2008) 360

$$h_{1,WW}^{\perp g} \ll f_{1,WW}^{\perp g} \quad \text{for } k_\perp \ll Q_s, \qquad h_{1,WW}^{\perp g} = 2f_{1,WW}^{\perp g} \quad \text{for } k_\perp \gg Q_s$$

Metz, Zhou, 2011

Since there are so different expectations inside and outside the saturation region, it would thus be very interesting to study dijet DIS at a high-energy EIC

Pisano, D.B., Brodsky, Buffing & Mulders, JHEP 10 (2013) 024

Note: for dijet in DIS the result does not require large $N_c$

Dijet in DIS is also the golden channel for the gluon Sivers effect at EIC

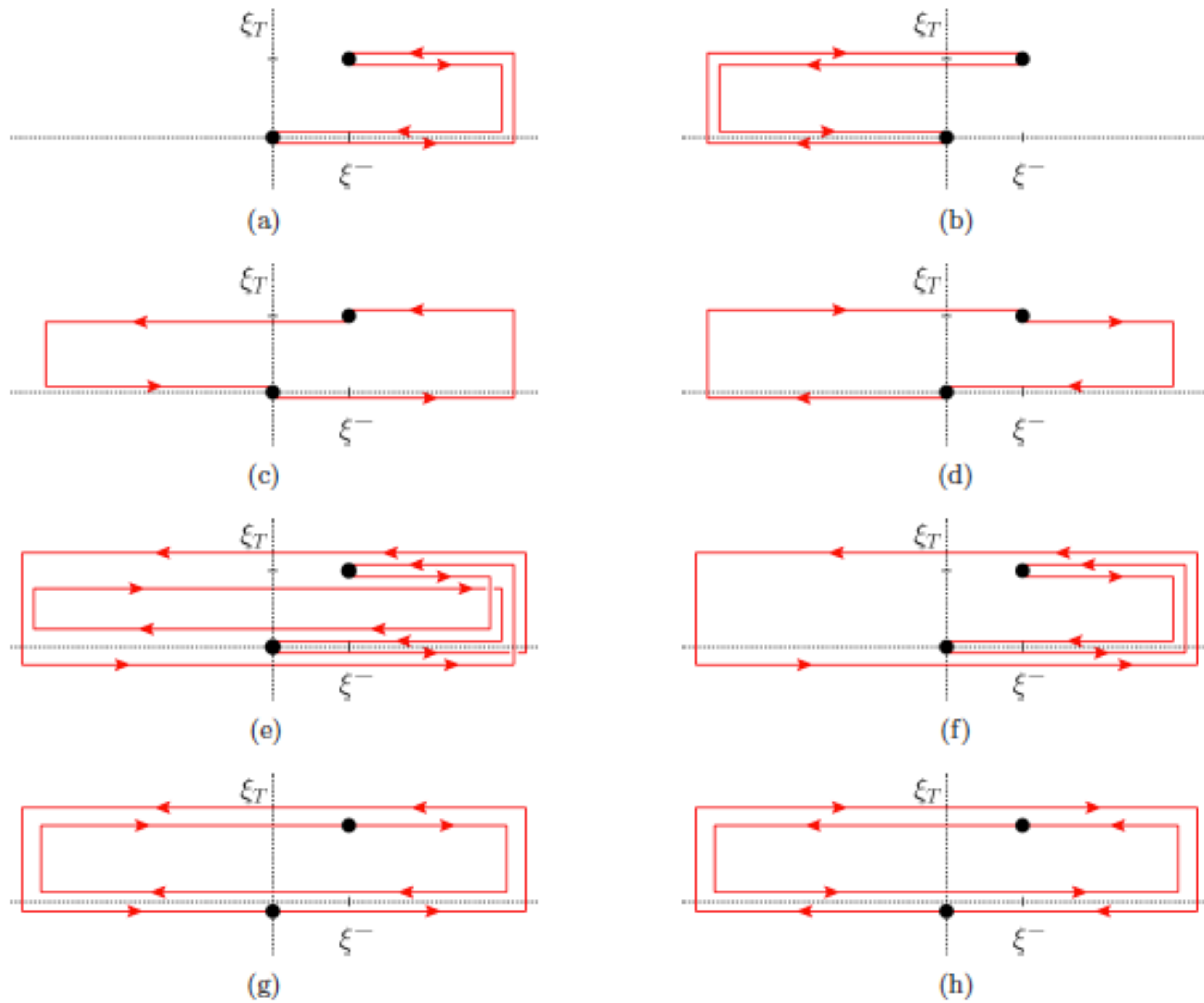
# Nonuniversality

For dijet in pA the result does require large $N_c$. More generally there are 5 TMDs:

$$h_1^{\perp g[U]}(x, p_T^2) \;=\; h_1^{\perp g(A)}(x, p_T^2) + \sum_{c=1}^{4} C_{GG,c}^{[U]}\, h_1^{\perp g(Bc)}(x, p_T^2)$$

Note: without ISI/FSI it can still be nonzero

Buffing, Mukherjee, Mulders, 2013



# Small x

What about TMD factorization breaking in pA to dijets?

In the small-x limit factorization breaking contributions may become suppressed

for nearly back-to-back di-jets ( $q_\perp \equiv |k_\perp + k'_\perp| \ll |k_\perp|, |k'_\perp| \equiv P_\perp$ ) :

$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2k_\perp d^2k'_\perp} = \sum_a x_p f_{a/p}(x_p) \sum_i F^{(a,i)}_{g/A}(x_A, q_\perp)\ H^{(i)}_{ag}\ \exp\left[-b_i \ln^2\left(\frac{P_\perp}{q_\perp}\right)\right]$$

$F^{(a,i)}$ : obtained from two-independent unintegrated gluons $G^{(1)}$ and $G^{(2)}$ (with different operator definitions)

Dominguez, Marquet, Xiao and Yuan (2011)

hard matrix elements

CSS-like Sudakov factors

Mueller, Xiao and Yuan (2013)

"One-Loop Factorization for Inclusive Hadron Production in p-A Collisions in the Saturation Formalism", Chirilli, Xiao, Yuan, PRL 108 (2012) 122301

# Conclusions

# Conclusions

- Significant recent developments on TMD factorization and evolution:
  - New TMD factorization expressions [Collins, 2011 & Echevarria-Idilbi-Scimemi, 2012]
  - Improvements through resummations to NNLL level [Echevarria *et al.*, 2013/4]

- Consequences of TMD evolution has been studied (to varying levels of accuracy) for Higgs production including the effect of linear gluon polarization

- TMD evolution calculations find 2-5% level contributions from linearly polarized gluons at Higgs mass scale

- Effect of linearly polarized gluons at Higgs mass scale smaller than current cross section uncertainty (NNLL+NNLO), also $p_T$ resolution below 10 GeV poor

- Future data from LHC on $\chi_{c/b0}$ and $\eta_{c/b}$ production and from heavy quark pair or dijet production in DIS at a high-energy EIC can shed light on $h_1^{\perp g}$ effects

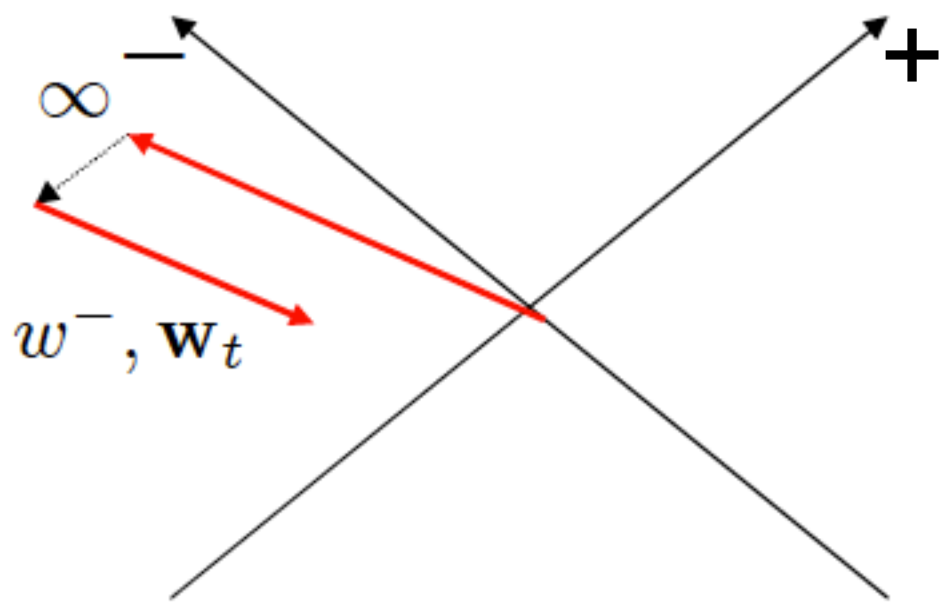
- Comparison of small and large x especially interesting

# Back-up slides

# Scale dependence of TMDs

QCD corrections will also attach to the Wilson line, which needs renormalization
This determines the change with renormalization scale μ

Wilson lines not smooth → cusp anomalous dimension
[Polyakov '80; Dotsenko & Vergeles '80; Brandt, Neri, Sato '81; Korchemsky, Radyushkin '87]




As a regularization of rapidity/LC divergences of a *lightlike* Wilson line, in JCC's TMD factorization the path is taken off the lightfront, the variation in rapidity determines the change with ζ

$$\tilde{f}^{[\mathcal{U}]}(x, b_T^2; \zeta, \mu)$$

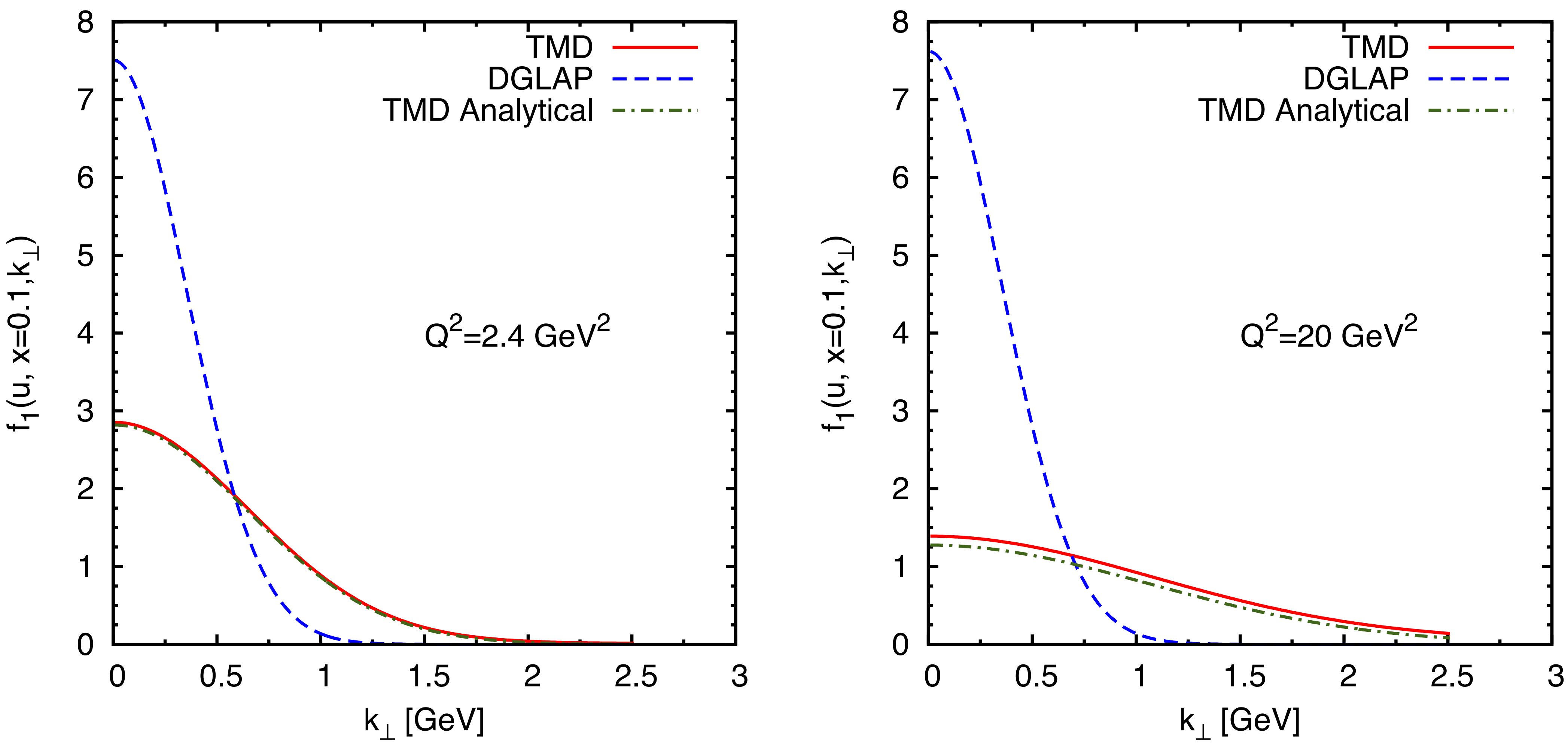
Two important consequences:

- yields energy evolution of TMD observables
- allows for calculation of the TMDs on the lattice
  Musch, Hägler, Engelhardt, Negele & Schäfer, 2012

# Comparing TMD and DGLAP evolution

At small Q $S_{NP}$ dominates the evolution

For larger Q the evolution becomes perturbative




Anselmino, Boglione, Melis
PRD 86 (2012) 014028

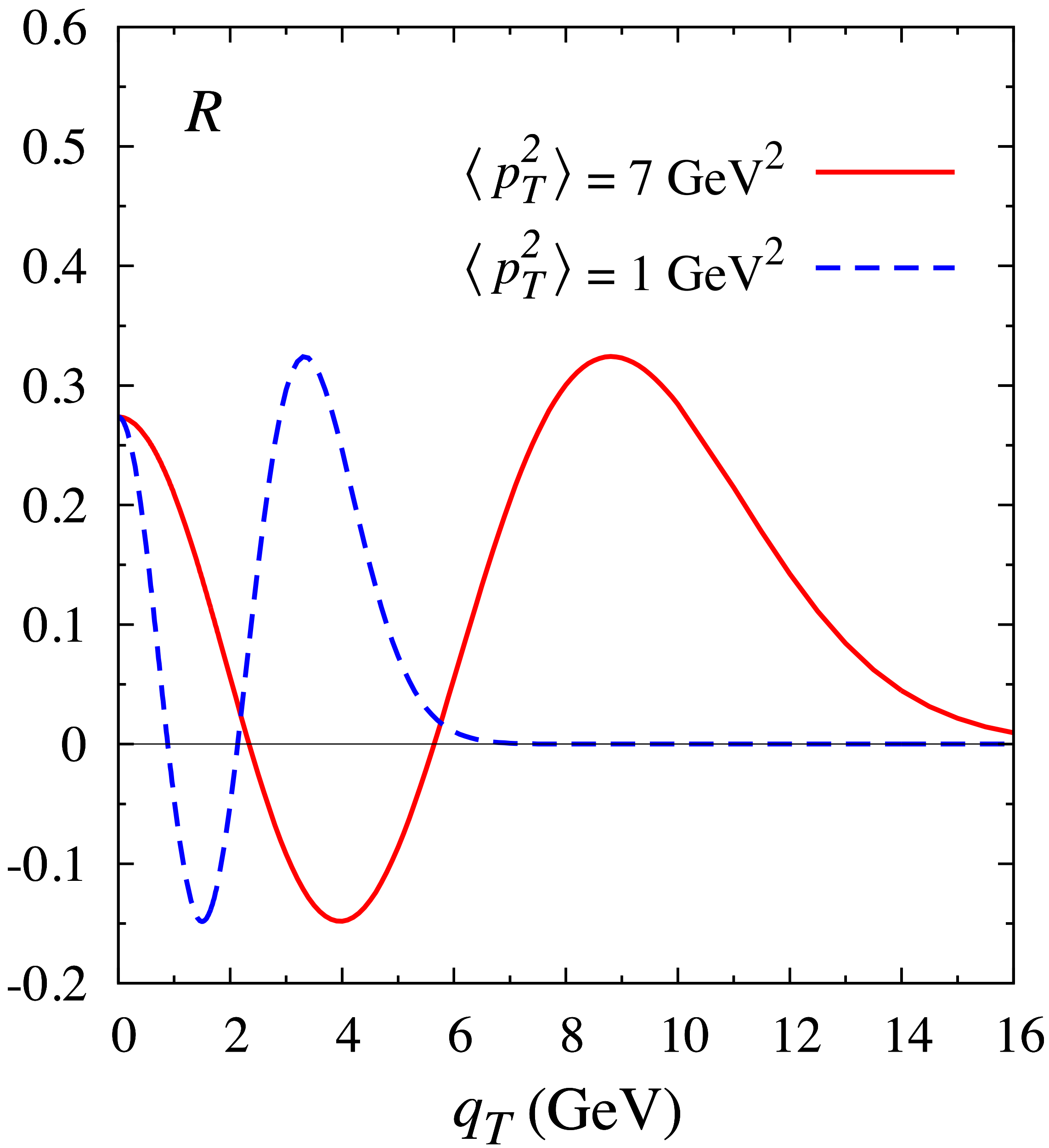
Difference between DGLAP and TMD evolution is large
in this limited range of Q: from 1.5 to 4.5 GeV

All curves evolved from
$Q^2$ = 1 GeV$^2$

Angular independent cross section is of the form:

$$\frac{d\sigma}{dq_T} \propto [1 \pm R(q_T)] \qquad (+ \text{ for } H^0; - \text{ for } A^0)$$

$$R = \frac{\mathcal{C}[w_H h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]}$$




Characteristic modulation (double node)

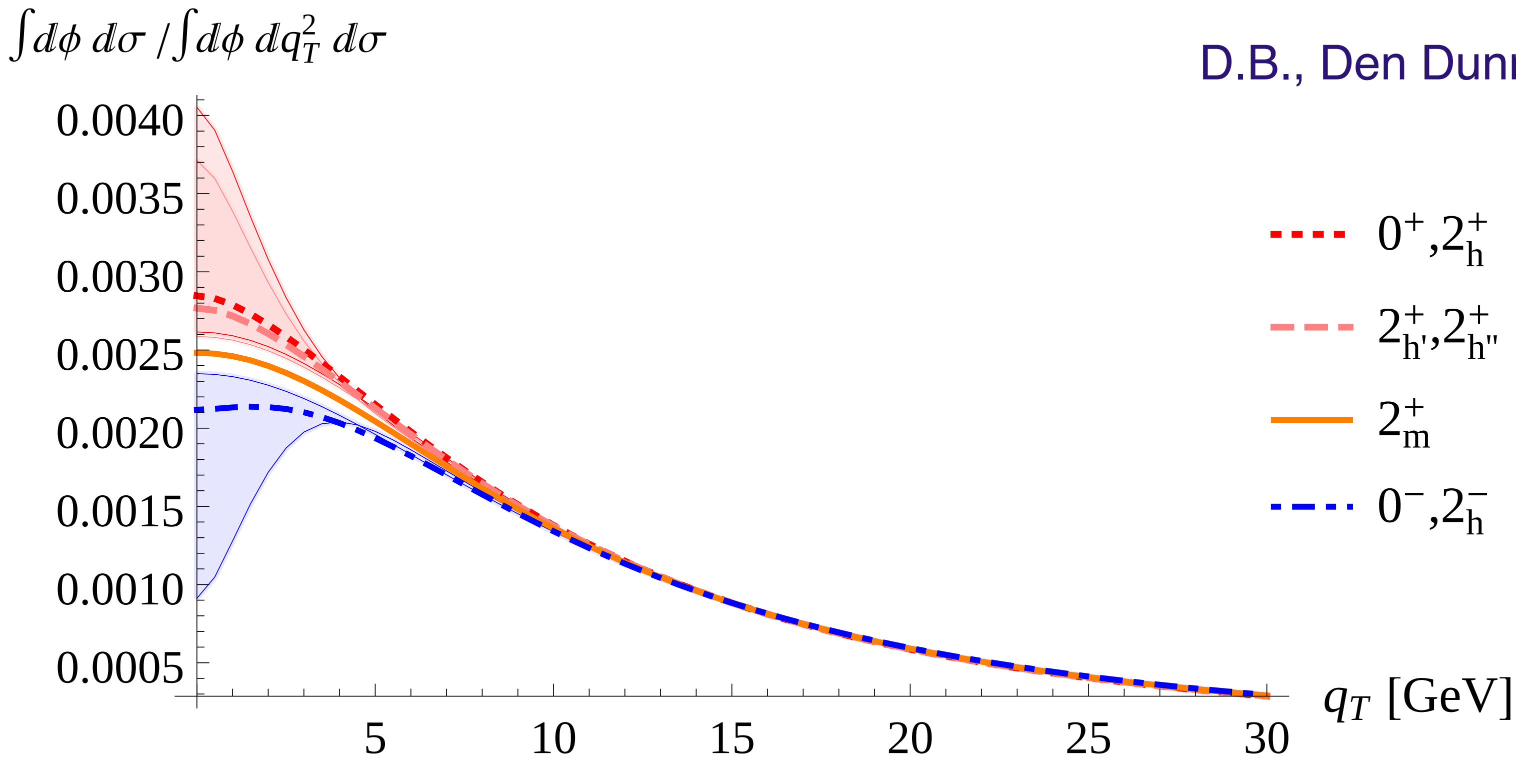
Overall sign determined by the parity of the Higgs

[DB, Den Dunnen, Pisano, Schlegel, Vogelsang, ’12]

Here a model function for $h_1^{\perp g}$ is used that is close to its bound for larger $q_T$

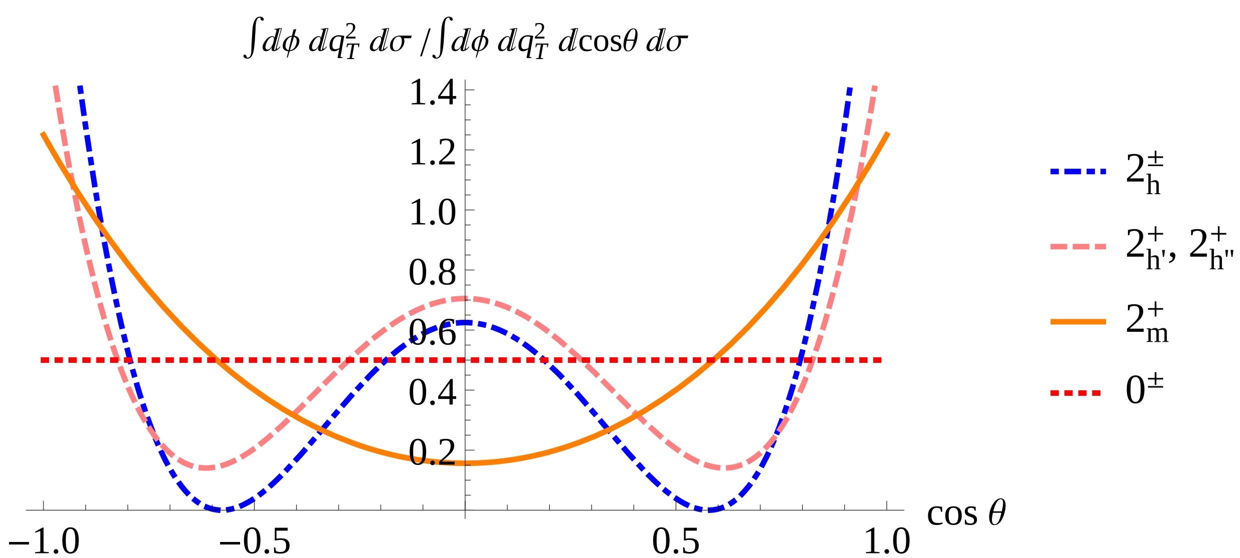
# Effects on Higgs production

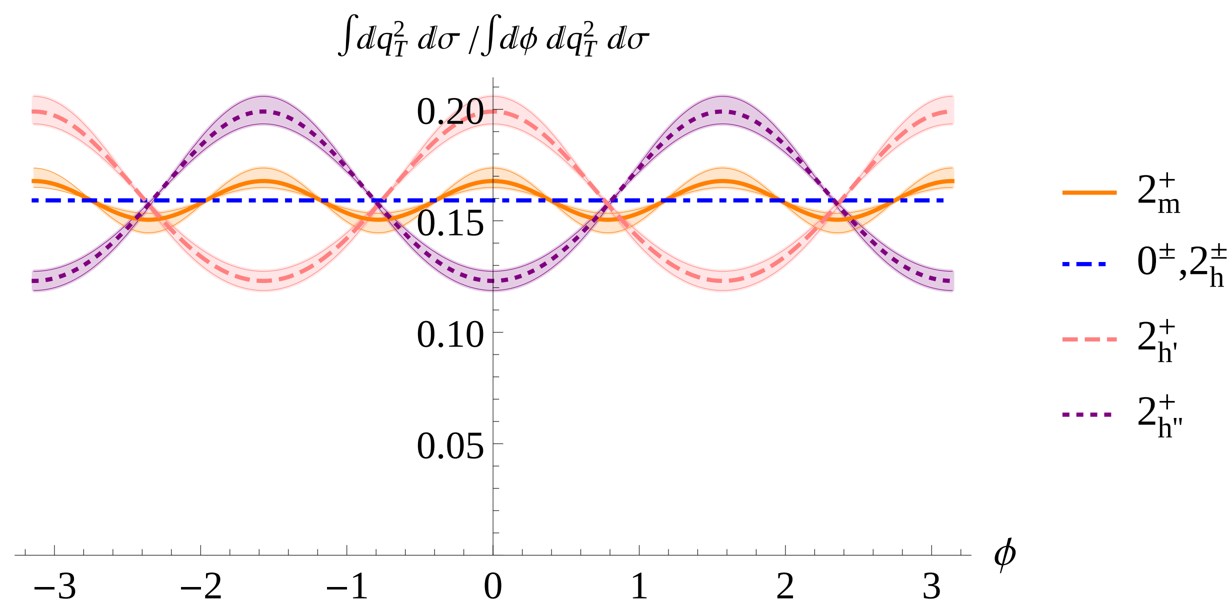
## Modification of the transverse momentum distribution




D.B., Den Dunnen, Pisano, Schlegel '13

## Polarization allows one to distinguish between spin-0 and spin-2 Higgs boson possibilities (more options than currently with Monte Carlo studies)

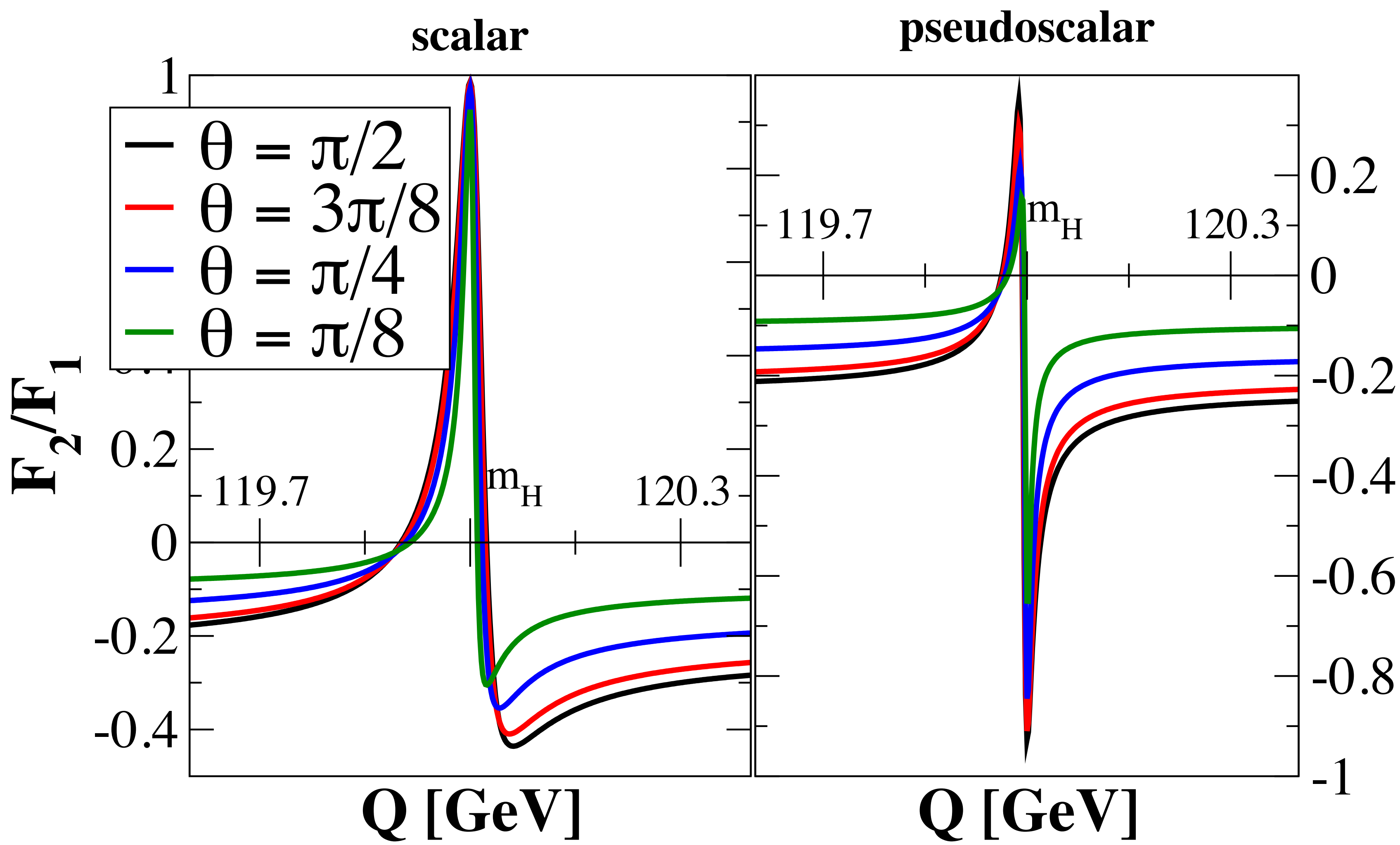



$0^-$ and $2_m^+$ are essentially excluded by LHC already

## $gg \to \gamma\,\gamma$

$$\int d\phi \frac{d\sigma}{d^4q\,d\Omega} \propto \left[1 + \frac{F_2}{F_1} R(q_T)\right]$$




Discernable only in a narrow region around the Higgs mass (here: $m_H$=120 GeV)

[DB, Den Dunnen, Pisano, Schlegel, Vogelsang, '12]

# $gg \rightarrow \gamma\gamma$

$$\int d\phi \frac{d\sigma}{d^4q\, d\Omega} \propto \left[1 + \frac{F_2}{F_1} R(q_T)\right]$$

Energy resolution becomes important
Assume ΔQ=0.5 GeV