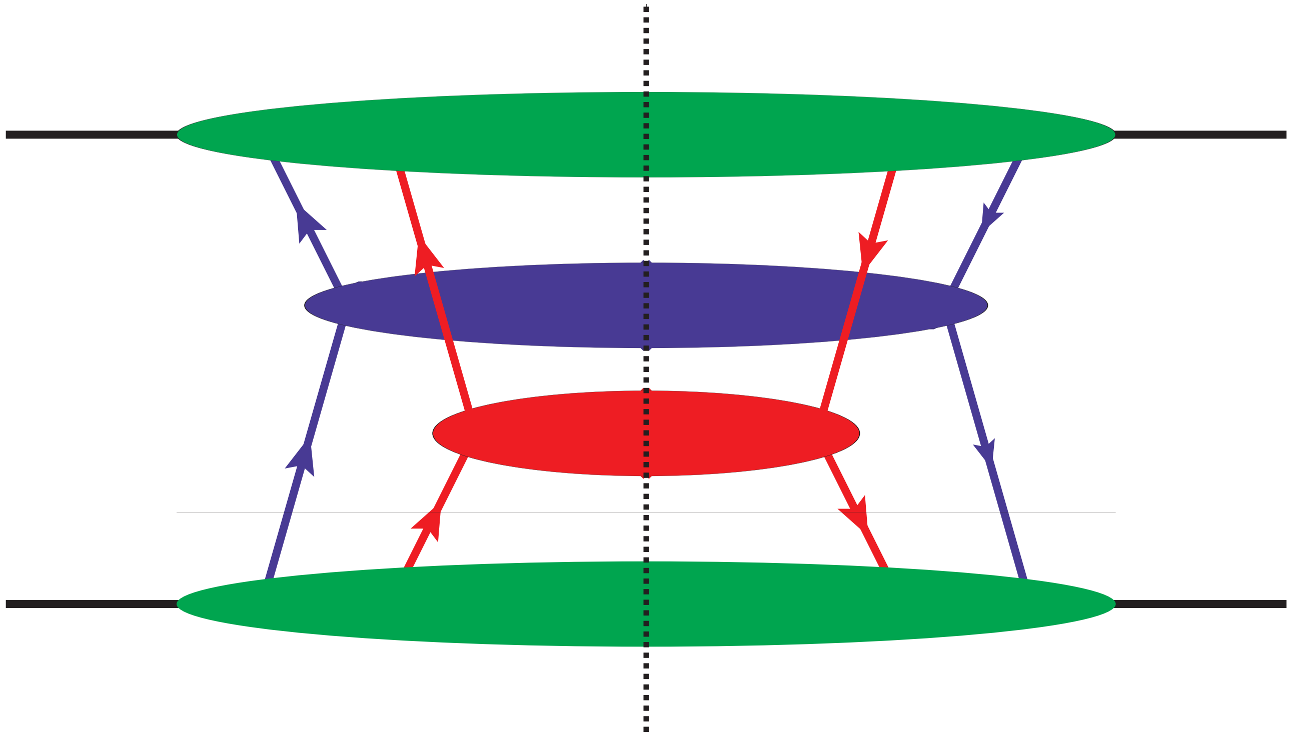
DPS: polarization, azimuthal dependence and proton size effects

Tomas Kasemets
Nikhef / VU

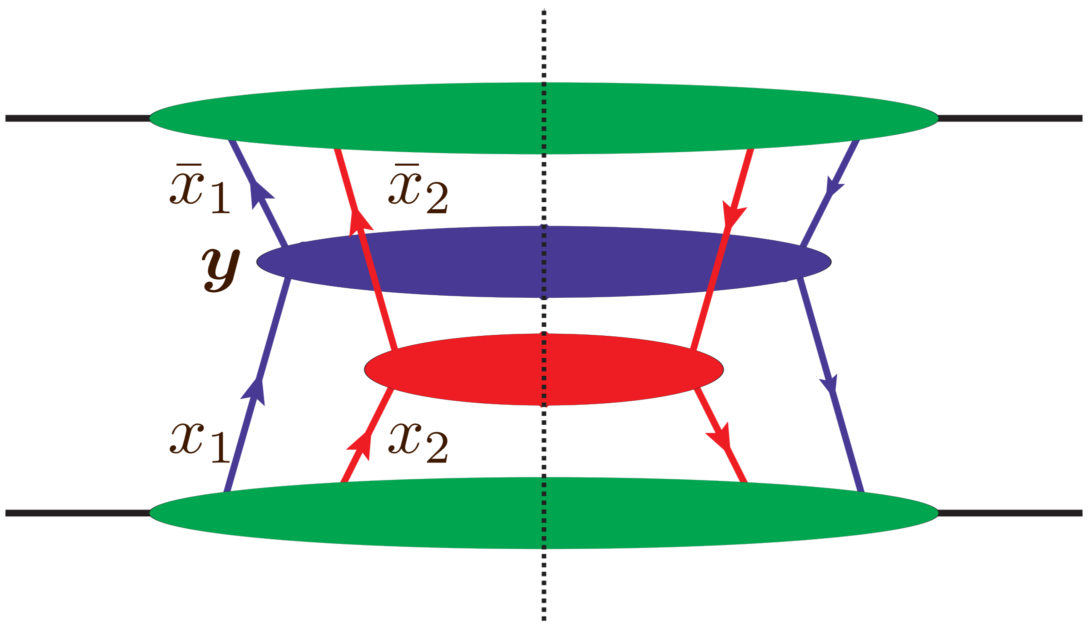


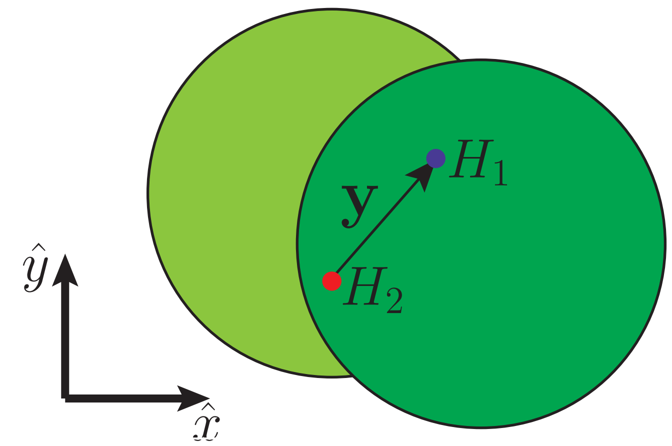
Echevarria, TK, Mulders, Pisano, arXiv:1501.07291
Diehl, TK, Keane, arXiv:1401.1233

Quarkonia 2016 - Trento, March 4, 2016

DPS cross section

- Example: DPS cross-section





- QCD requires inclusion of the transverse separation between hard scatterings

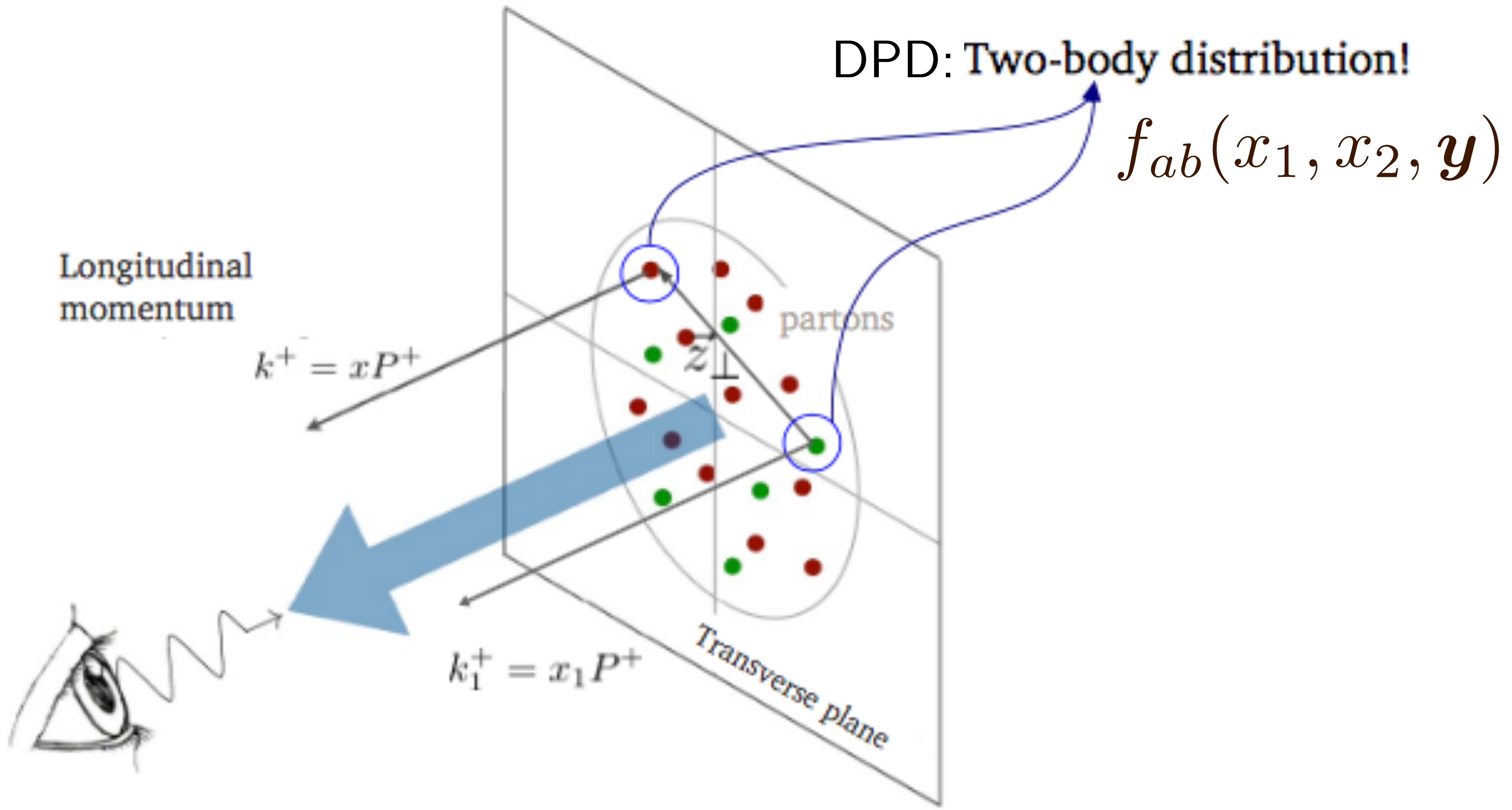
Paver, Treleani, 1982; Mekhfi, 1985;
Diehl, Ostermeier, Schäfer, 2011

$$d\sigma_{DPS} \sim d\sigma_1 d\sigma_2 \int d^2y \left[f_{qq}(x_1, x_2, y) f_{\bar{q}\bar{q}}(\bar{x}_1, \bar{x}_2, y) + \ldots \right]$$

Double Parton Distributions (DPDs)

- + New phenomena!?!

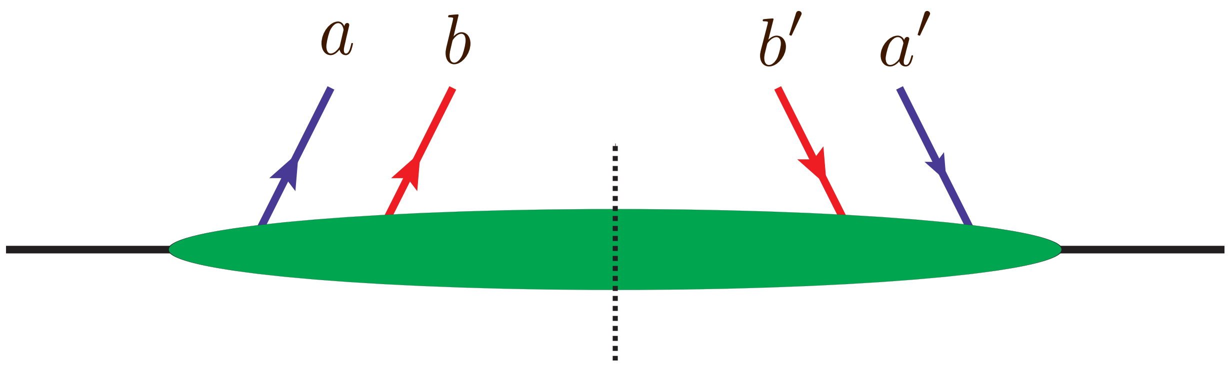
Double parton distributions



New way to access information on the non-perturbative structure of the PROTON!

from Matteo Rinaldi, MPI@LHC 2015

Correlations in DPS

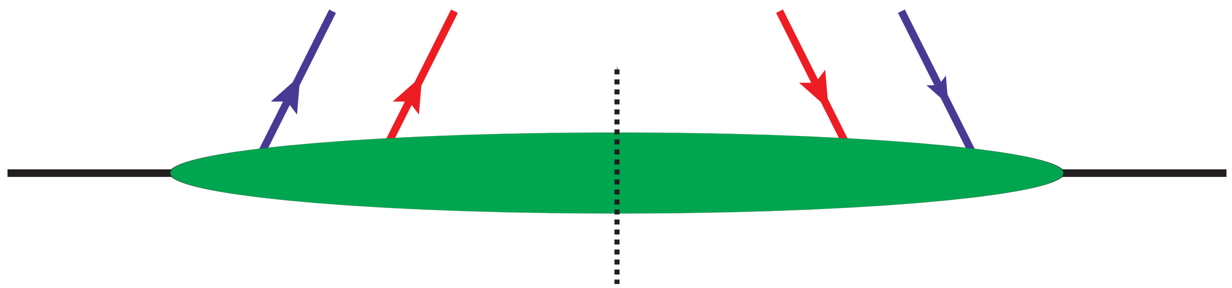


$$(a+b) = (a'+b') \not\Leftrightarrow \begin{cases} a = a' \\ b = b' \end{cases}$$

- Color
- Fermion number interference
- Spin (polarization)
  - longitudinal
  - transverse/linear
- Flavor interference
- Between $\boldsymbol{y}$ and x's
- Parton type and $\boldsymbol{y}$
- Between x's

Road to the pocket formula

- What approximations goes into σ_{eff}



- Approximations step 1: Separation of transverse dependence

$$F_{ab}(x_1, x_2, \boldsymbol{y}; \mu) = f_{ab}(x_1, x_2; \mu) G(\boldsymbol{y})$$

- Approximations step 2: Separation of longitudinal dependence

$$f_{ab}(x_1, x_2) = f_a(x_1) f_b(x_2)$$

- Results in the (infamous) pocket formula

$$\sigma_{DPS} \sim \frac{\sigma_1 \sigma_2}{\sigma_{\text{eff}}}$$

- Both steps problematic and difficult to control or systematize
- What can we do beyond σ_{eff}?

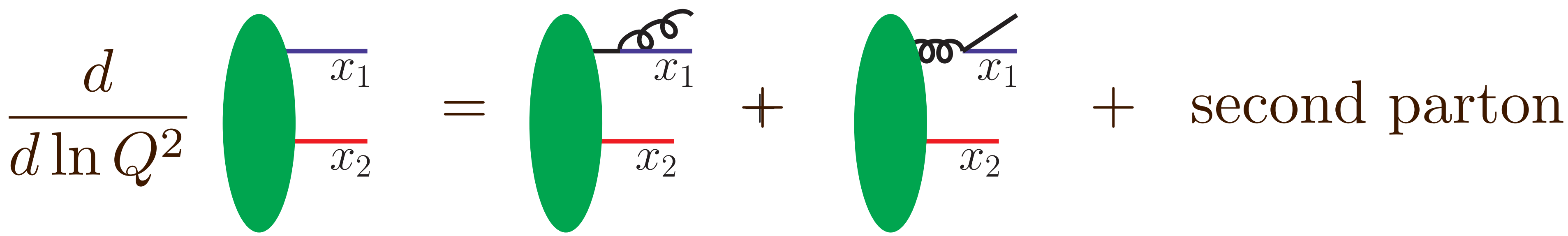
Towards a DPS license

Towards a DPS license

Towards a DPS license

Evolution of DPDs

$$\frac{df_{qq}(x_1, x_2, y; Q)}{d \ln Q^2} = \frac{\alpha_s(Q)}{2\pi} \Big[P_{qq} \otimes_1 f_{qq} + P_{qg} \otimes_1 f_{gq} + P_{qq} \otimes_2 f_{qq} + P_{qg} \otimes_2 f_{qg} \Big] \,,$$



- Convolution with Altarelli-Parisi splitting kernels

$$P_{ab}(\,.\,) \otimes_1 f_{bc}(\,.\,, x_2, y; Q) = \int_{x_1}^{1-x_2} \frac{dz}{z} P_{ab}\left(\frac{x_1}{z}\right) f_{bc}(z, x_2, y; Q) \,,$$

- Analogously for polarized partons
- Separate branchings - expect evolution to wash out correlations

Transverse dependence of DPDs

- Evolution of $\boldsymbol{y}$ dependence
  - Unpolarized DPDs
  - Need initial condition (DPDs at initial scale)
- Gaussian ansatz, longitudinal — transverse interplay
- Ansatz: DPDs in terms of GPDs

$$F_{ab}(x_1, x_2, \boldsymbol{y}) = \int d^2\boldsymbol{b} f_a(x_1, \boldsymbol{b}) f_b(x_2, \boldsymbol{b} + \boldsymbol{y})$$

$$f_a(x, \boldsymbol{b}) = f_a(x) \frac{1}{4\pi h_a(x)} \exp\left[-\frac{b^2}{4h_a(x)}\right] \qquad h_a(x) = \alpha'_a \ln\frac{1}{x} + B_a$$

- $h_a(x)$ connected to measurements of exclusive t slopes

$$f_a(x, \boldsymbol{r}) = f_a(x) \exp\left[-h_a(x)\boldsymbol{r}^2\right] \qquad \boldsymbol{r}^2 = -t$$

Transverse dependence of DPDs

- Gives ansatz for transverse dependence of the DPDs at initial scale:

$$F_{ab}(x_1, x_2, \boldsymbol{y}) = f_a(x_1)\, f_b(x_2) \times \frac{1}{4\pi h_{ab}(x_1, x_2)} \exp\left[-\frac{\boldsymbol{y}^2}{4\, h_{ab}(x_1, x_2)}\right]$$

$$h_{ab}(x_1, x_2) = \alpha'_a \ln\frac{1}{x_1} + \alpha'_b \ln\frac{1}{x_2} + B_a + B_b$$

- Parameters from GPD fits ($q^{\pm} = q \pm \bar{q}$)

$$\alpha'_{q^-} = 0.9\,\text{GeV}^{-2}\,, \qquad B_{q^-} = 0.59\,\text{GeV}^{-2}\,,$$
$$\alpha'_{q^+} = 0.164\,\text{GeV}^{-2}\,, \qquad B_{q^+} = 2.4\,\text{GeV}^{-2}\,,$$
$$\alpha'_g = 0.164\,\text{GeV}^{-2}\,, \qquad B_g = 1.2\,\text{GeV}^{-2}$$

Diehl, Kugler, 2008

Diehl, Feldmann, Jakob, Kroll, 2005

- MSTW2008lo for single PDFs

Martin, Stirling, Thorne, Watt, 2009

Transverse dependence of DPDs

- Gives ansatz for transverse dependence of the DPDs at initial scale:

$$F_{ab}(x_1, x_2, \boldsymbol{y}) = f_a(x_1)\, f_b(x_2) \times \frac{1}{4\pi h_{ab}(x_1, x_2)} \exp\left[-\frac{\boldsymbol{y}^2}{4 h_{ab}(x_1, x_2)}\right]$$

$$h_{ab}(x_1, x_2) = \alpha'_a \ln\frac{1}{x_1} + \alpha'_b \ln\frac{1}{x_2} + B_a + B_b$$

- Parameters from GPD fits ($q^{\pm} = q \pm \bar{q}$)

$$\alpha'_{q^-} = 0.9\,\text{GeV}^{-2}, \qquad B_{q^-} = 0.59\,\text{GeV}^{-2},$$

$$\alpha'_{q^+} = 0.164\,\text{GeV}^{-2}, \qquad B_{q^+} = 2.4\,\text{GeV}^{-2},$$

$$\alpha'_g = 0.164\,\text{GeV}^{-2}, \qquad B_g = 1.2\,\text{GeV}^{-2}$$

Diehl, Kugler, 2008

Diehl, Feldmann, Jakob, Kroll, 2005

- MSTW2008lo for single PDFs

Martin, Stirling, Thorne, Watt, 2009

Transverse dependence of DPDs

- Gives ansatz for transverse dependence of the DPDs at initial scale:

$$F_{ab}(x_1, x_2, \boldsymbol{y}) = f_a(x_1)\, f_b(x_2) \times \frac{1}{4\pi h_{ab}(x_1, x_2)} \exp\left[-\frac{\boldsymbol{y}^2}{4\, h_{ab}(x_1, x_2)} \right]$$

strength of correlation

$$h_{ab}(x_1, x_2) = \alpha'_a \ln \frac{1}{x_1} + \alpha'_b \ln \frac{1}{x_2} + B_a + B_b$$

- Parameters from GPD fits ($q^{\pm} = q \pm \bar{q}$)

$$\alpha'_{q^-} = 0.9\,\mathrm{GeV}^{-2}\,, \qquad B_{q^-} = 0.59\,\mathrm{GeV}^{-2}\,,$$
$$\alpha'_{q^+} = 0.164\,\mathrm{GeV}^{-2}\,, \qquad B_{q^+} = 2.4\,\mathrm{GeV}^{-2}\,,$$
$$\alpha'_g = 0.164\,\mathrm{GeV}^{-2}\,, \qquad B_g = 1.2\,\mathrm{GeV}^{-2}$$

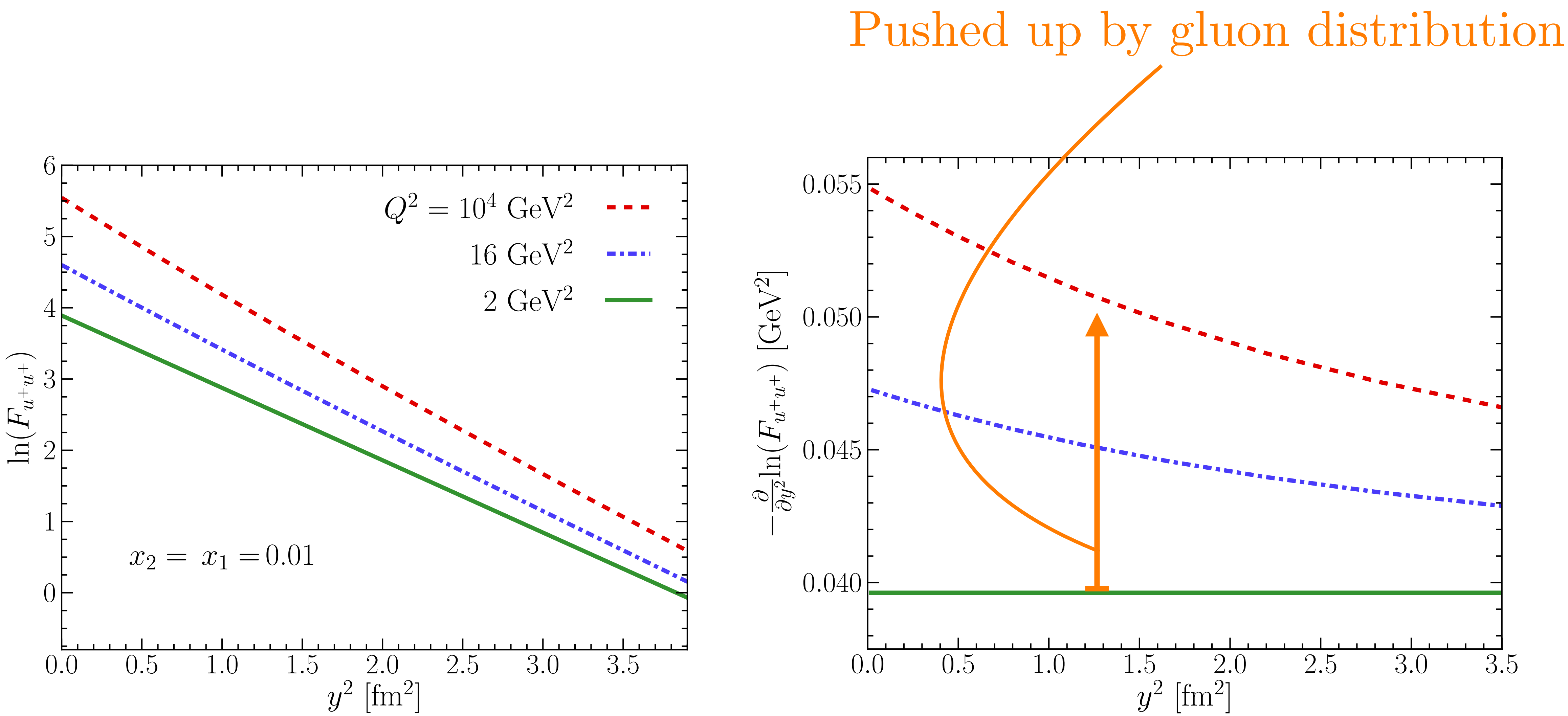
Diehl, Kugler, 2008

Diehl, Feldmann, Jakob, Kroll, 2005

- MSTW2008lo for single PDFs

Martin, Stirling, Thorne, Watt, 2009

- Evolution of u^+u^+ distribution

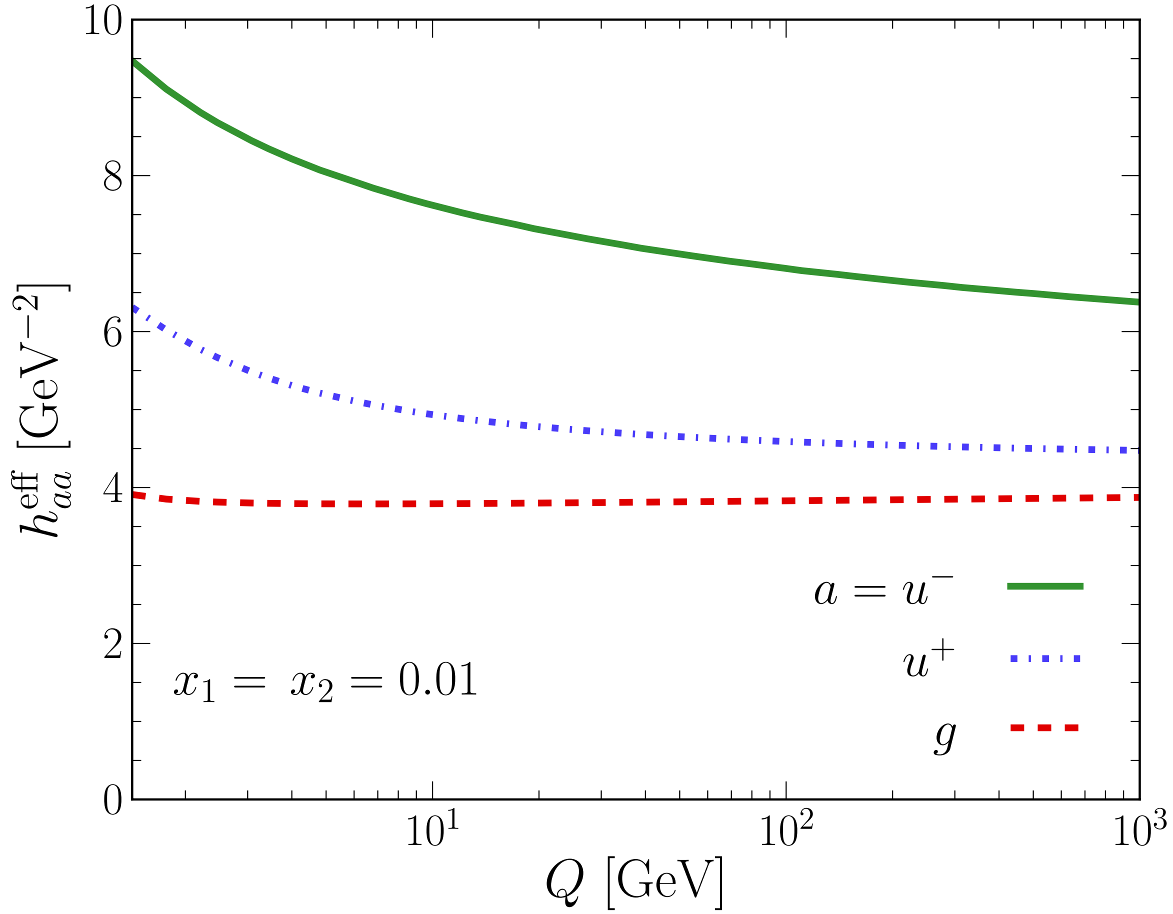


- Distributions stays approximately Gaussian up to high scale

  ⇒ Allows us to examine the evolution of the exponent h

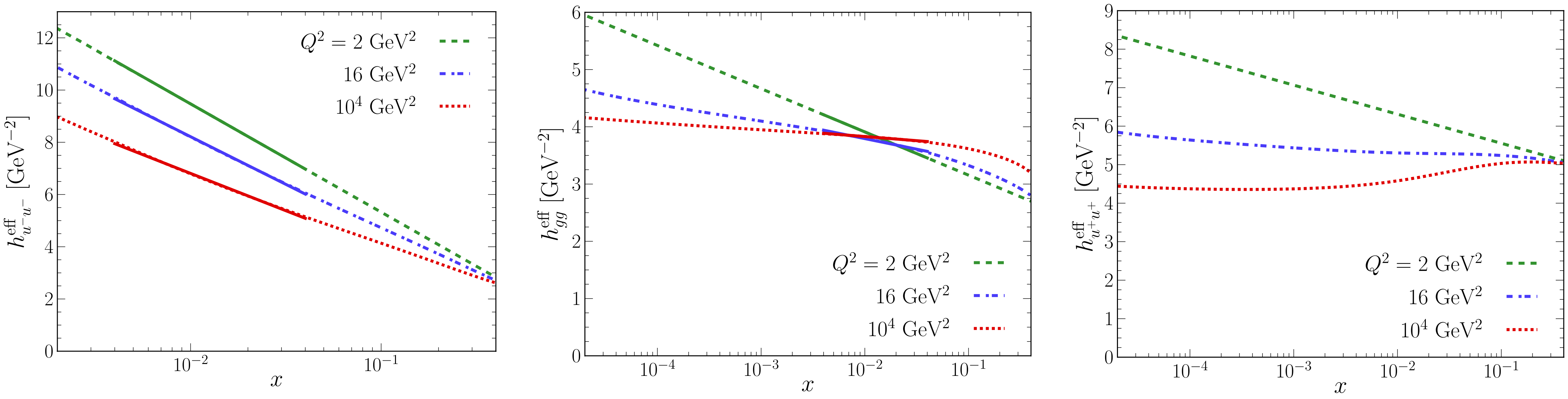
- Taking the log of the distributions gives us access to the exponential

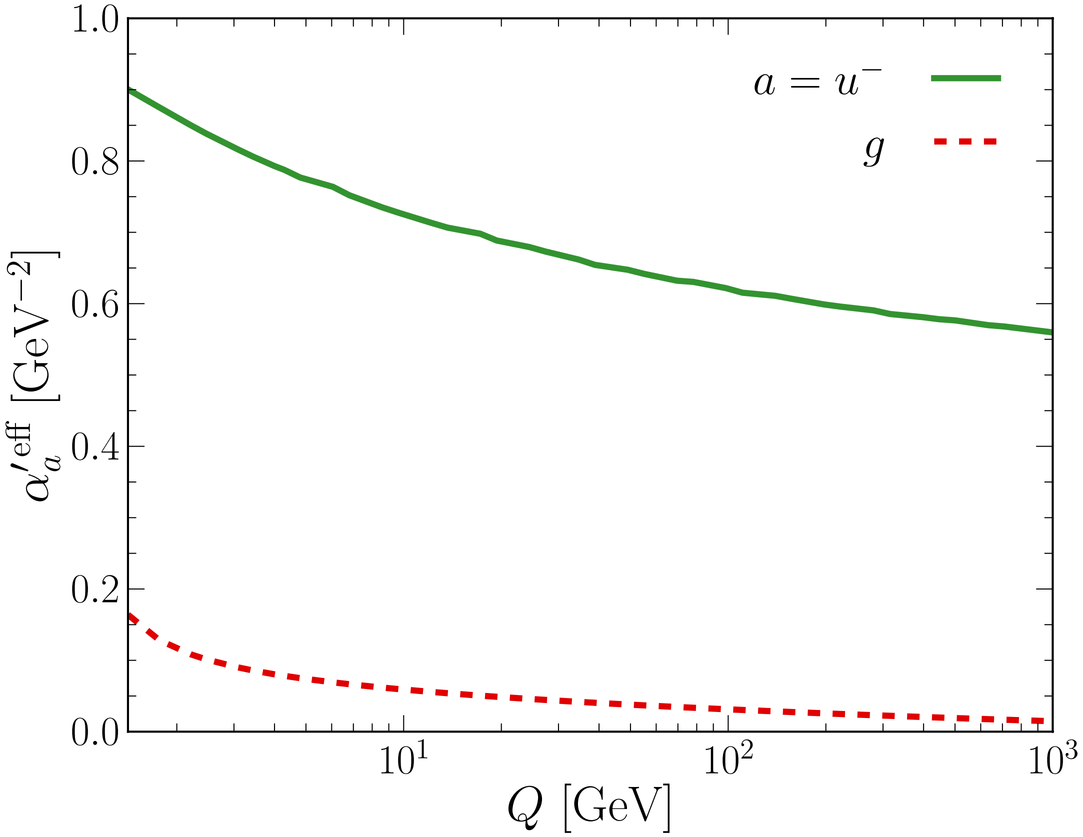
$$\left.\frac{\ln F_{aa}(x,x,y) - \ln F_{aa}(x,x,0)}{y^2}\right|_{y=0.4\,\mathrm{fm}} = -\frac{1}{4\,h^{\mathrm{eff}}_{aa}(x,x)}$$



- Gluon width evolve slowly
- u^- and u^+ decrease
- Differences in transverse dependence up to large scale
  - even between u^+ and gluon

- Differences at the initial scale to a large extent remain after evolution up to larger scales





- x dependence of h
- u^- and g approx. linear in lnx (away from the large x region)
- Fit α'_a describing correlation between x_1, x_2 and $\boldsymbol{y}$
- Slow decrease in correlations
- u^+ slope highly dependent on x region

- Correlations remain up to large scales - transverse profile changes

Color correlations:

- Color singlet and octet distributions

$${}^1F_{q_1,\bar{q}_2} \to (\bar{q}_2 \mathbb{1} q_2)(\bar{q}_1 \mathbb{1} q_1) \qquad {}^8F_{q_1,\bar{q}_2} \to (\bar{q}_2 t^a q_2)(\bar{q}_1 t^a q_1)$$

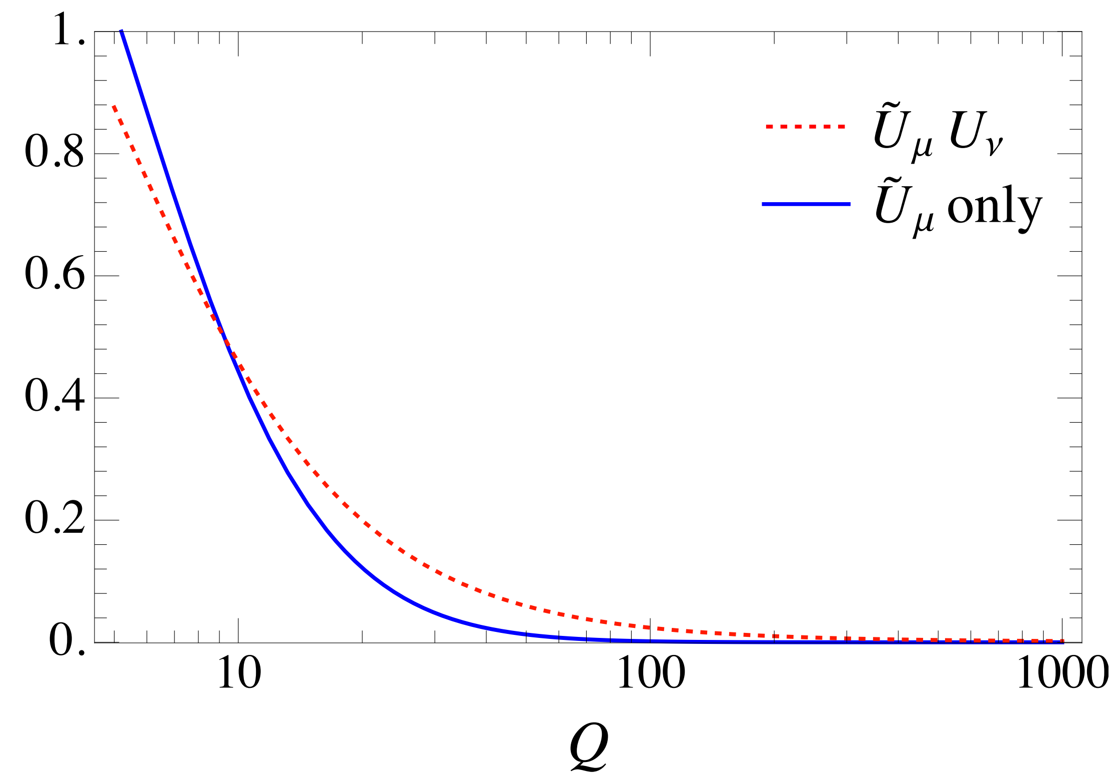
- Color correlations enter cross section weighted by a Sudakov factor

$\Rightarrow$ Suppressed at large Q

Manohar, Waalewijn, 2012;
Mekhfi, Artru, 1985

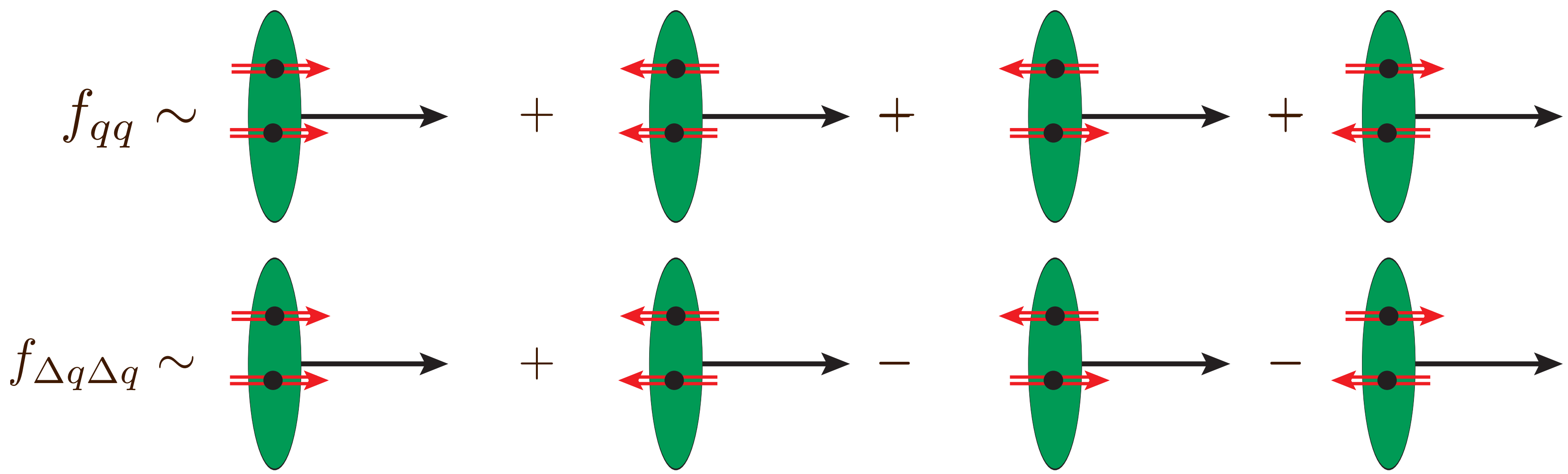
$$\tilde{U}_\mu(\Lambda, Q) = \exp\left[-\frac{\alpha_s C_A}{2\pi} \ln^2 \frac{Q^2}{\Lambda^2}\right]$$

- Color correlations should not be relevant at large scales.
- Interpretation:
Transportation of color over hadronic distance



Manohar, Waalewijn, 2012

Polarization



- Two partons in an unpolarized proton can each be unpolarized, longitudinally polarized and linearly/transversely polarized,
  - Correlations between spin, transverse momenta and separation of the two partons

    Mekhfi, 1985; Diehl, Schäfer, 2011; Diehl, Ostermeier, Schäfer, 2011
  - Several polarized DPDs which contribute to DPS cross sections
  - Large in model calculations

    Rinaldi, Scopetta, Traini, Vento, 2014; Chang, Manohar, Waalewijn, 2011
- Changes total cross sections, distributions of final state particles and cause azimuthal asymmetries/spin asymmetries

  Manohar, Waalewijn, 2011; Diehl, TK, 2012; Echevarria, TK, Mulders, Pisano 2015

Polarized DPDs - direct effect on final state

- Longitudinal polarization:
  - Changes rate as well as rapidity and $|p_T|$ distributions
- Transverse quark/linear gluon polarization
  - Leads to azimuthal asymmetries
- Double Drell-Yan

$$d\sigma_{DPS}(pp \to ZZ \to l_1\bar{l}_1 l_2\bar{l}_2) \subset A\cos 2(\phi_1 - \phi_2) f_{\delta q \delta q} f_{\delta \bar{q} \delta \bar{q}}$$

TK, M. Diehl, 2012

for transversely polarize quarks

- Double $q\bar{q}$ production

$$d\sigma_{DPS}(pp \to c_1\bar{c}_1 c_2\bar{c}_2) \subset B\cos 2(\phi_1 - \phi_2) f_{\delta g g} f_{g \delta g} + C\cos 4(\phi_1 - \phi_2) f_{\delta g \delta g} f_{\delta g \delta g}$$

Echevarria, TK, Mulders, Pisano, 2015

for linearly polarized gluons

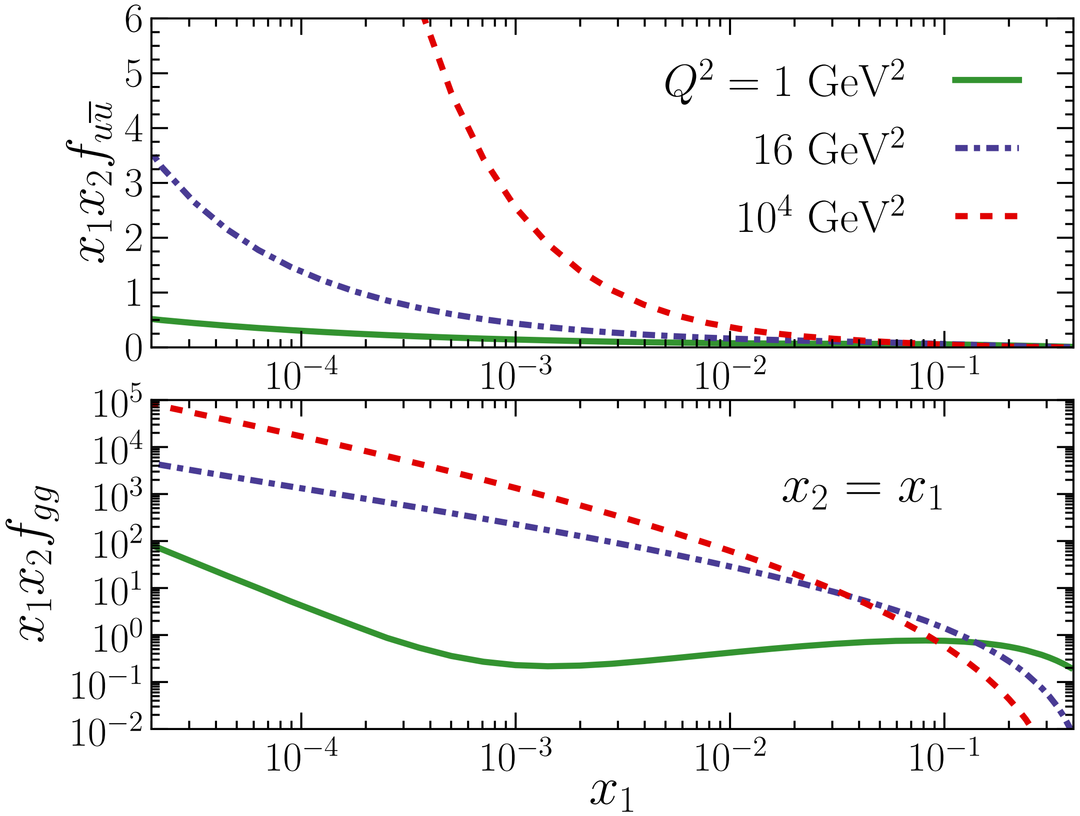
  - Linearly polarized gluons also affect the overall rate

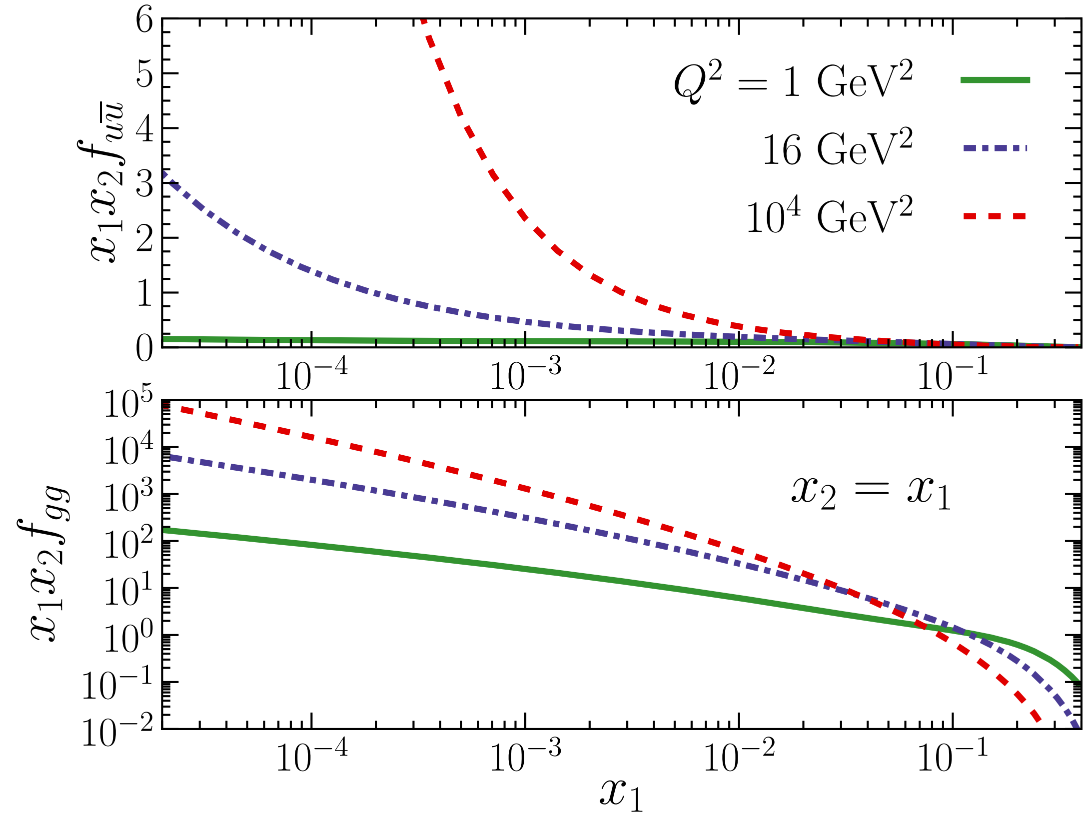
- Need an ansatz for the initial DPDs in order to study the effect of evolution on the polarization

$$f_{p_1 p_2}(x_1, x_2, \boldsymbol{y}; Q) = \tilde{f}_{p_1 p_2}(x_1, x_2; Q)\, G(\boldsymbol{y})\,,$$

  Not interested in normalization and set $G(\boldsymbol{y}) = 1$

- For unpolarized DPDs $\tilde{f}_{ab}(x_1, x_2; Q_0) = f_a(x_1; Q_0)\, f_b(x_2; Q_0)\,,$





MSTW2008lo GJR08lo

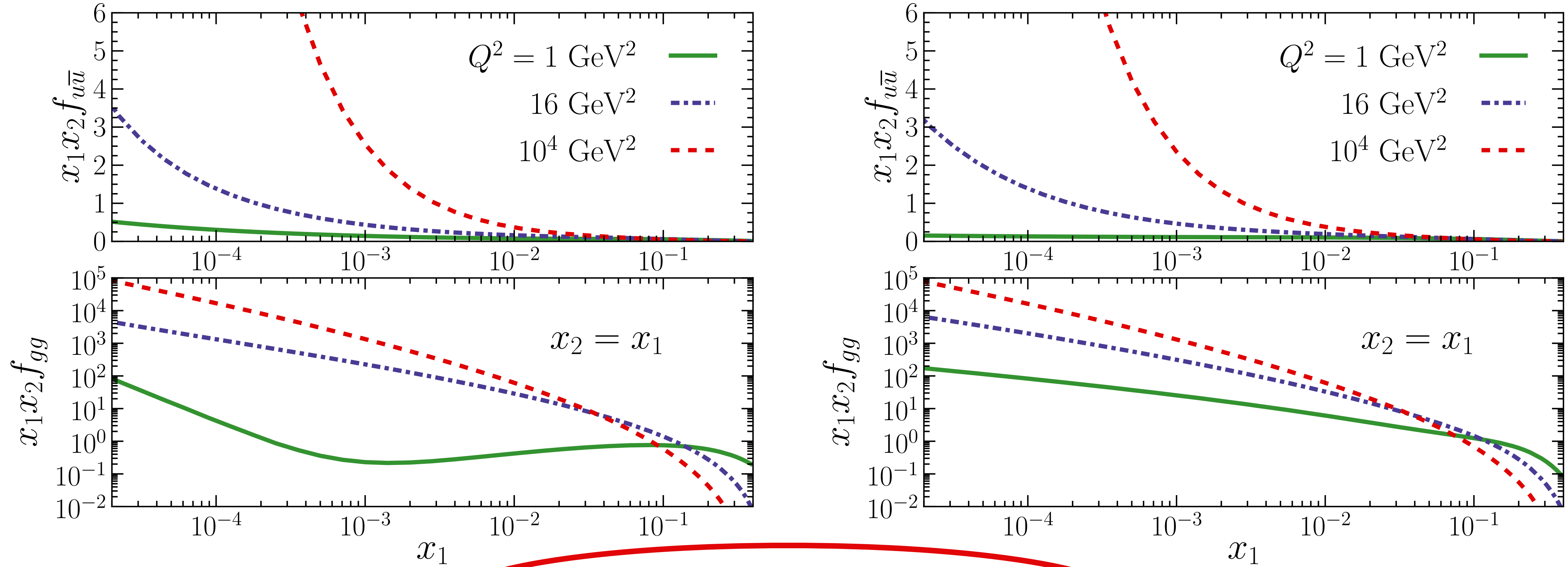
Martin, Stirling, Thorne, Watt, 2009; Glück, Jimenez-Delgado, Reya, 2007

- Need an ansatz for the initial DPDs in order to study the effect of evolution on the polarization

$$f_{p_1 p_2}(x_1, x_2, \boldsymbol{y}; Q) = \tilde{f}_{p_1 p_2}(x_1, x_2; Q)\, G(\boldsymbol{y})\,,$$

Not interested in normalization and set $G(\boldsymbol{y}) = 1$

- For unpolarized DPDs $\tilde{f}_{ab}(x_1, x_2; Q_0) = f_a(x_1; Q_0)\, f_b(x_2; Q_0)\,,$



Large difference for gluon

MSTW2008lo GJR08lo

Martin, Stirling, Thorne, Watt, 2009; Glück, Jimenez-Delgado, Reya, 2007

Max scenario

- Polarized DPDs more complicated
  - No single parton equivalence (parton-parton vs parton-proton)
- Upper bounds on polarized distributions from probability interpretation - stable under leading-order double DGLAP evolution
  - Analogue to Soffer bounds for polarized single PDFs

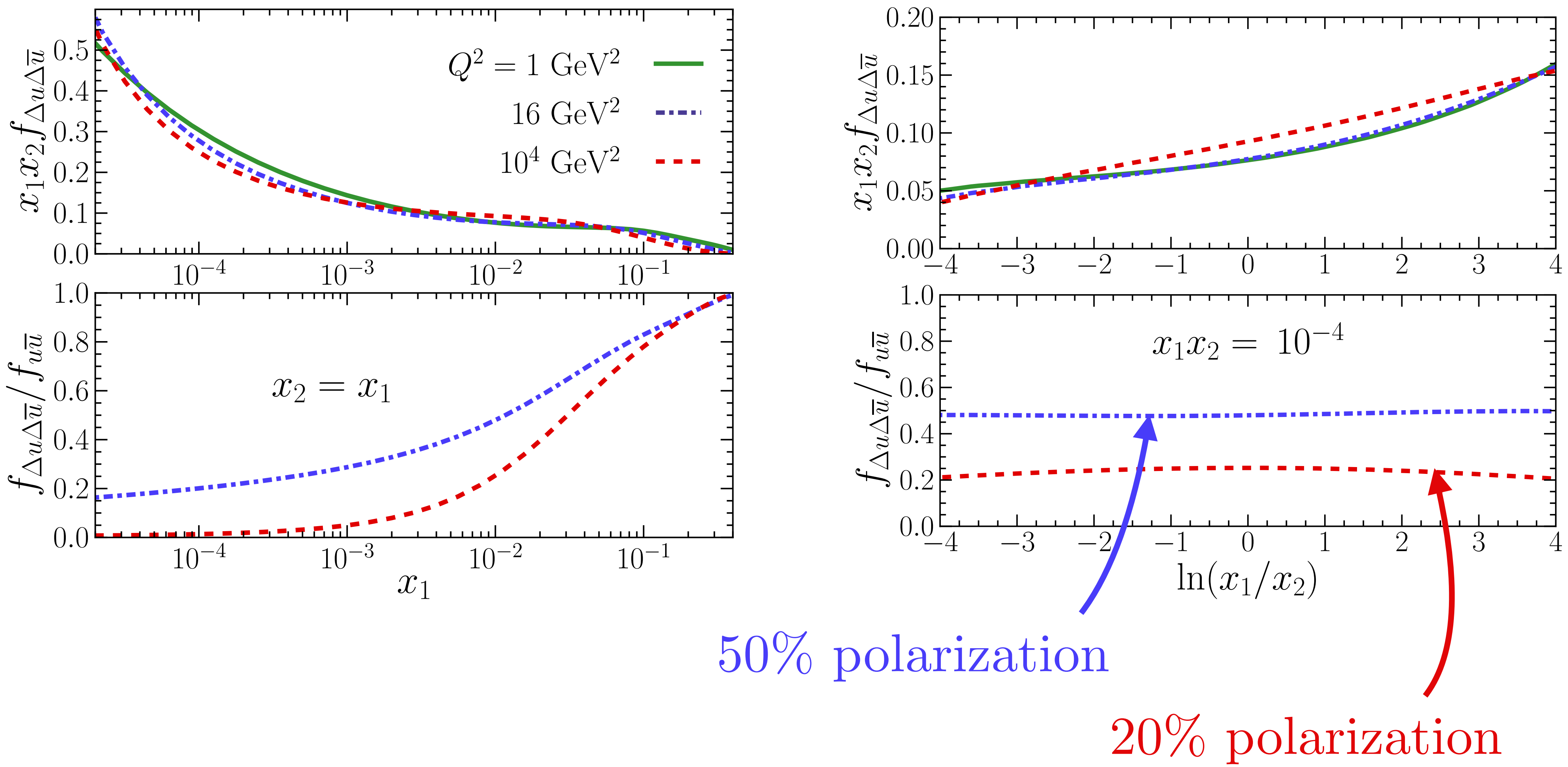
$$f_{ab} + h_{\delta a \delta b} - h^t_{\delta a \delta b} \pm \sqrt{(h_{\delta a b} + h_{a \delta b})^2 + (f_{\Delta a \Delta b} - h_{\delta a \delta b} - h^t_{\delta a \delta b})^2} \geq 0$$

$$f_{ab} - h_{\delta a \delta b} + h^t_{\delta a \delta b} \pm \sqrt{(h_{\delta a b} - h_{a \delta b})^2 + (f_{\Delta a \Delta b} + h_{\delta a \delta b} + h^t_{\delta a \delta b})^2} \geq 0$$

Diehl, TK, 2012

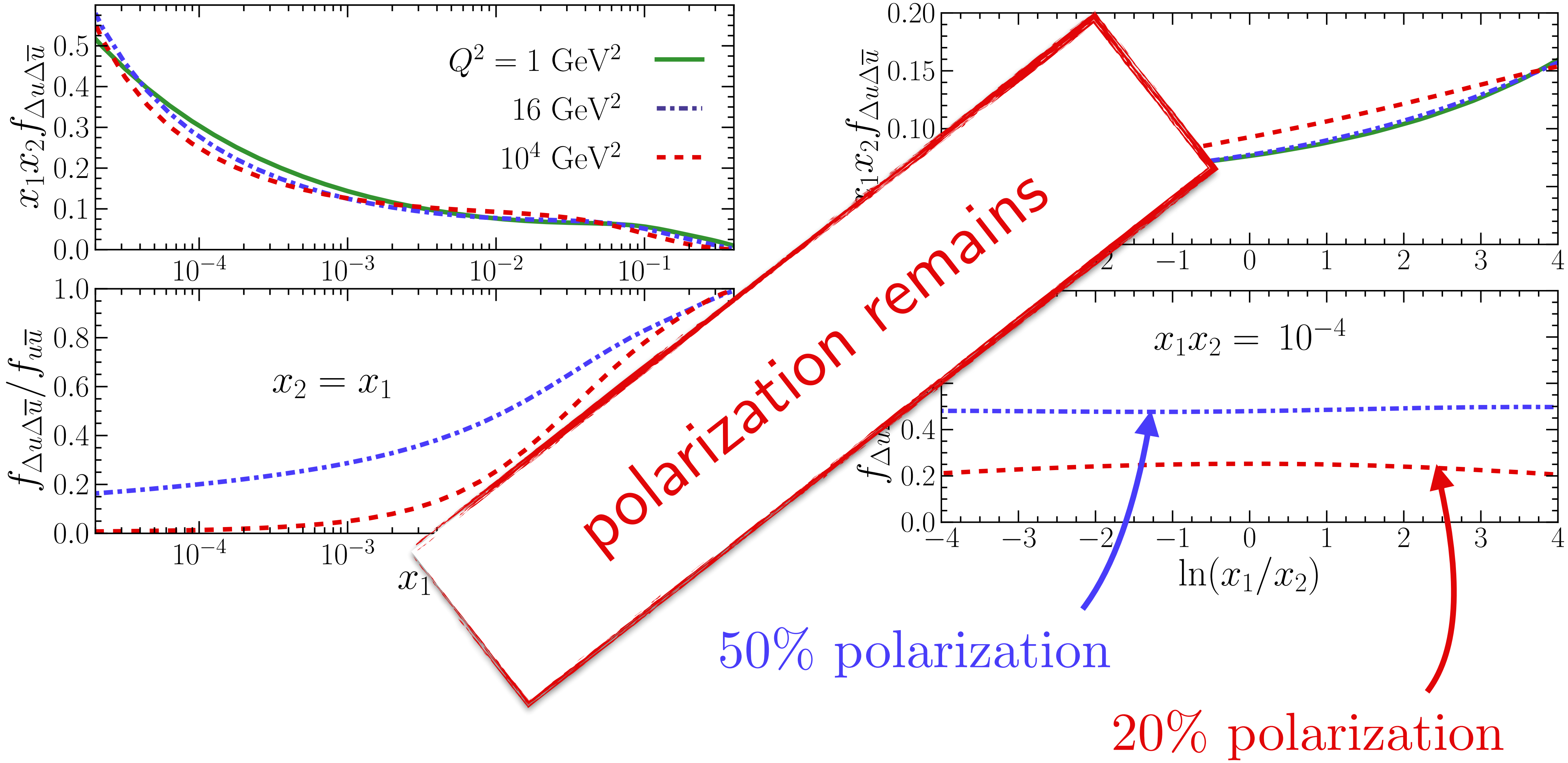
- *Max scenario* - each polarized DPD as large as possibly allowed
  - Polarized DPDs equal to unpolarized at starting scale

Longitudinal quark polarization



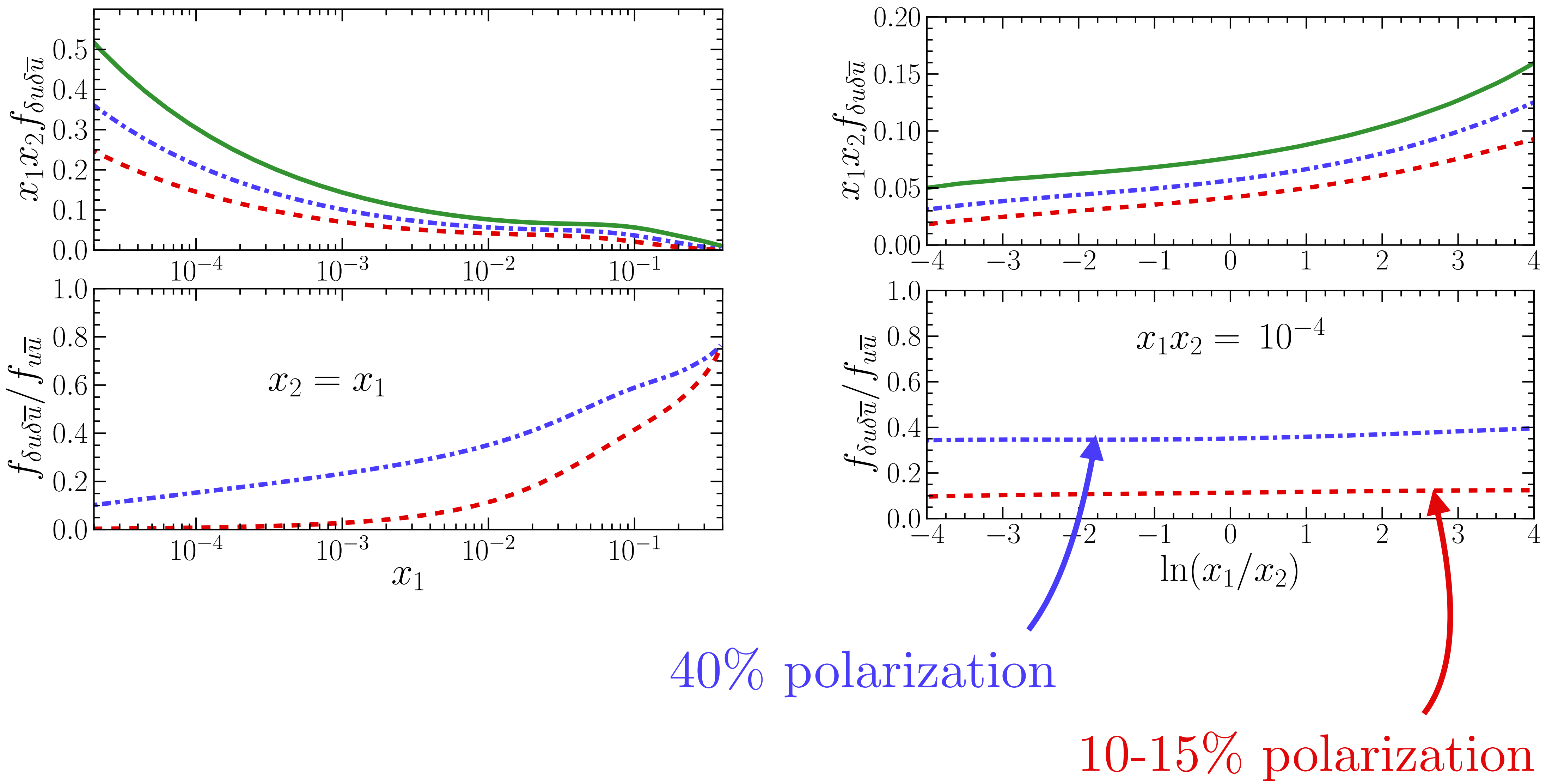
- *Max scenario*:
  - Large longitudinal polarization up to high scales in wide range of x_i
  - Degree of polarization flat in rapidity - generic feature in *max scenario*

Longitudinal quark polarization



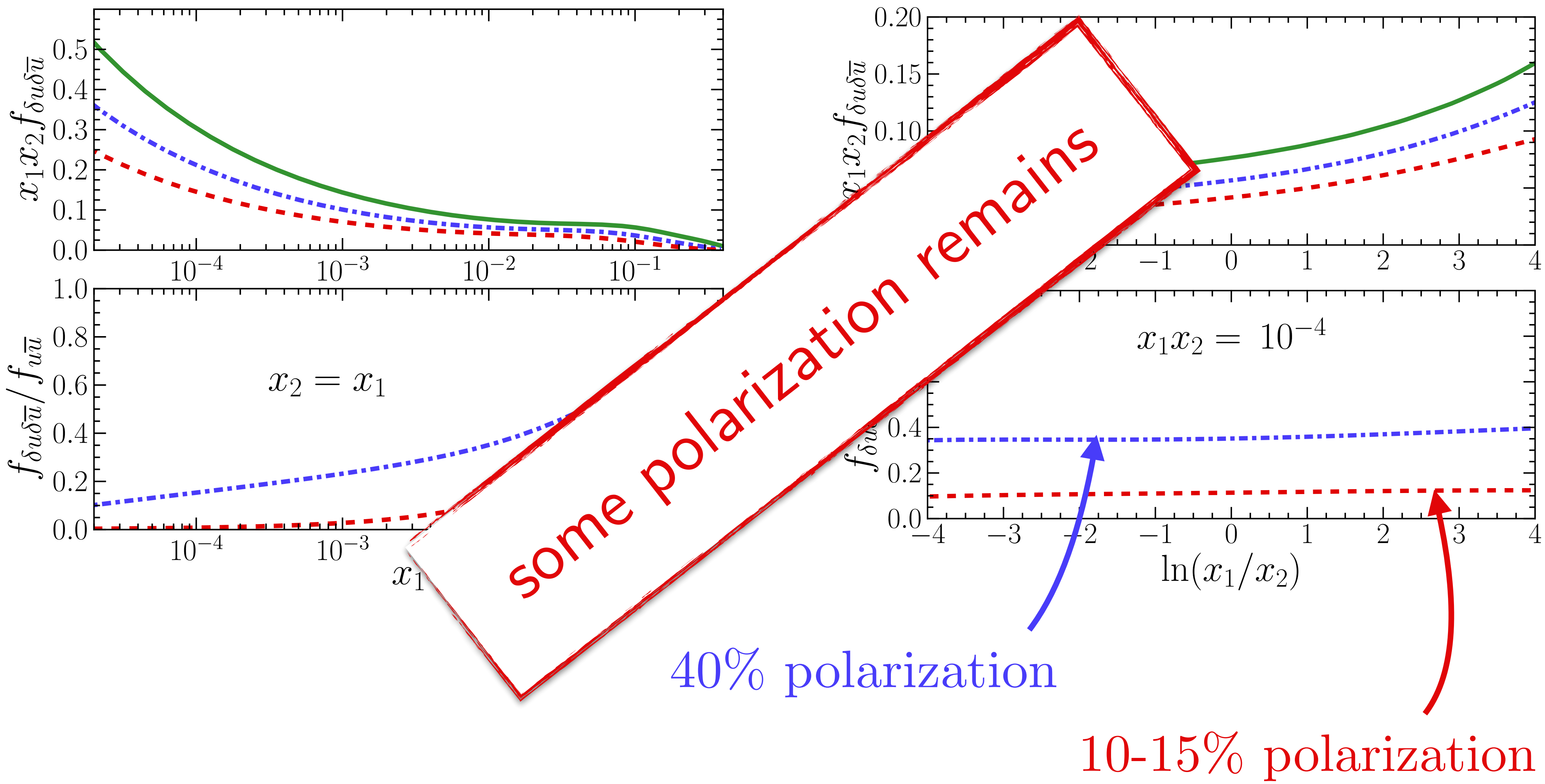
- *Max scenario*:
  - Large longitudinal polarization up to high scales in wide range of x_i
  - Degree of polarization flat in rapidity - generic feature in *max scenario*

Transverse quark polarization



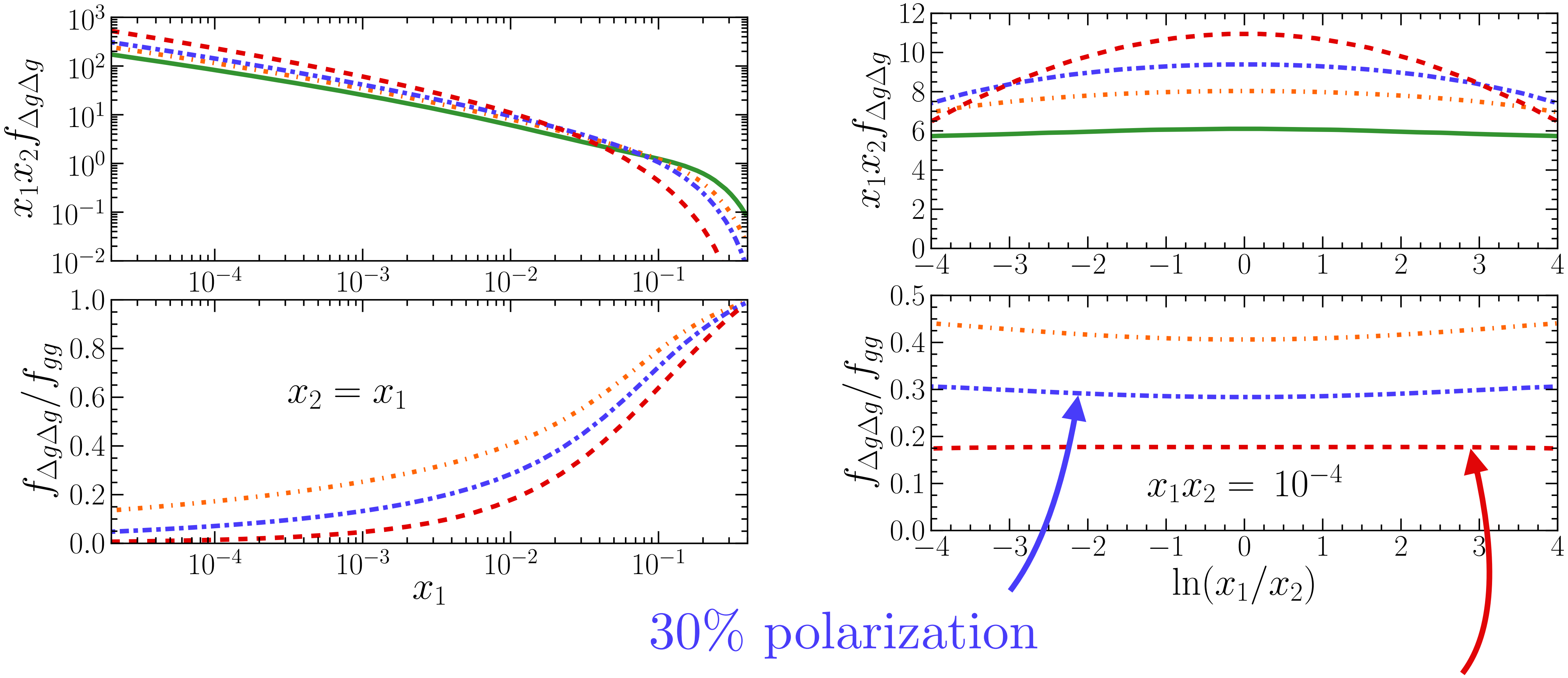
- *Max scenario*:
  - Sizable transverse polarization up to high scales in wide range of x_i
  - Degree of polarization flat in rapidity - generic feature in *max scenario*

Transverse quark polarization



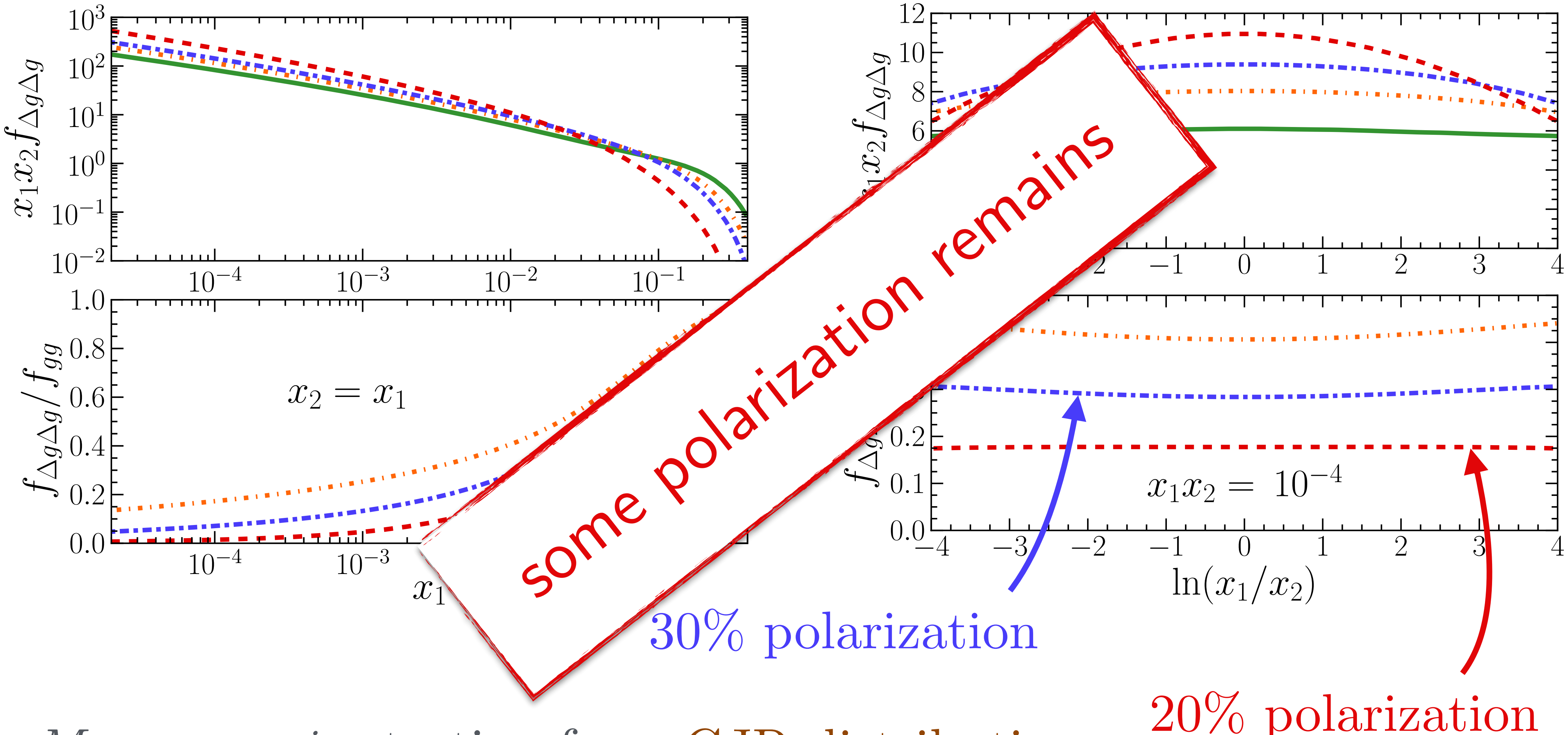
- *Max scenario*:
  - Sizable transverse polarization up to high scales in wide range of x_i
  - Degree of polarization flat in rapidity - generic feature in *max scenario*

Longitudinal gluon polarization



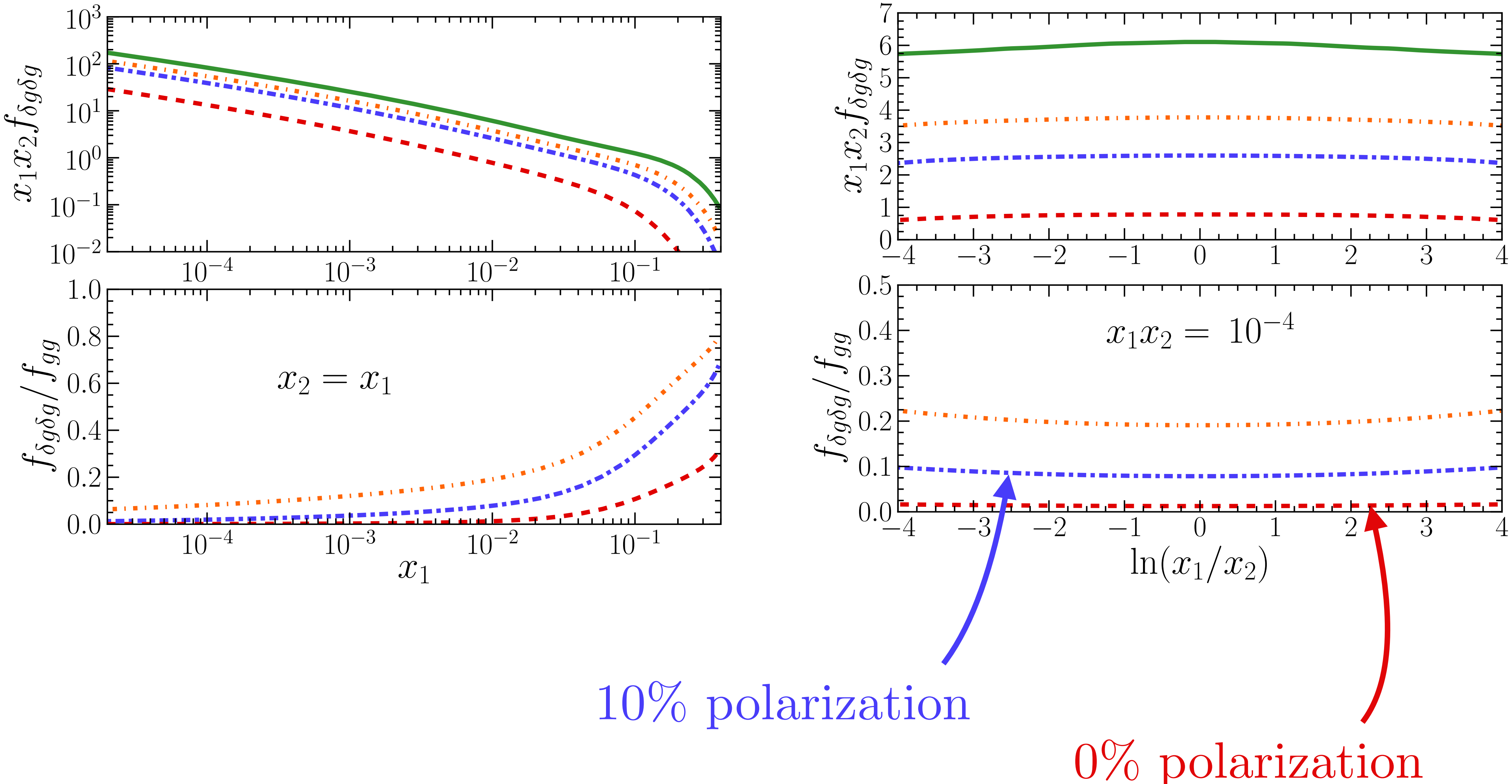
- *Max scenario* starting from GJR distributions
  - Much larger degree of polarization than with MSTW;
    - by factor 2-3 at larger scales
  - Difference mainly due to the unpolarized gluon PDF at low scales
  - Smaller degree of polarization than for quarks and antiquarks

Longitudinal gluon polarization



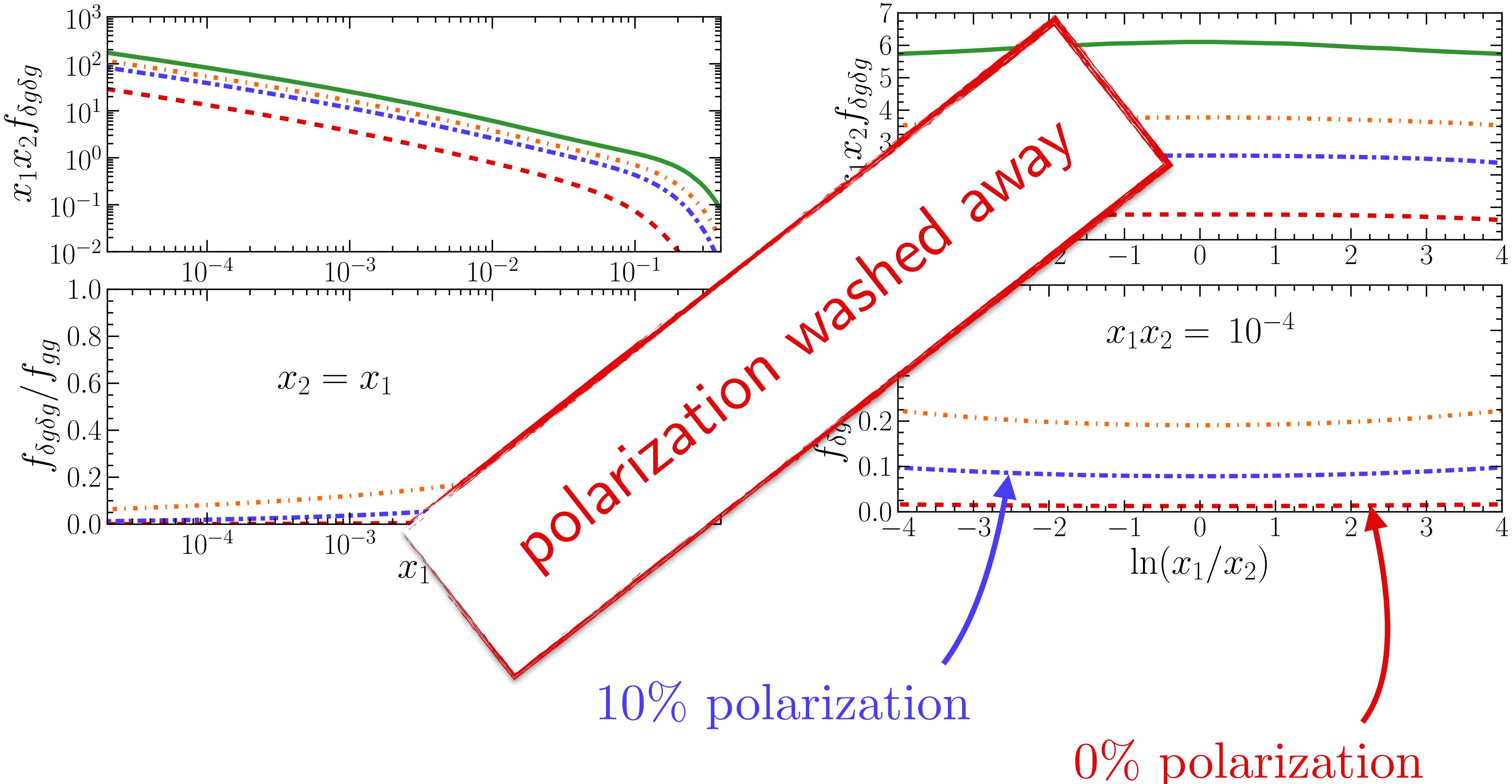
- *Max scenario* starting from GJR distributions
  - Much larger degree of polarization than with MSTW;
    - by factor 2-3 at larger scales
  - Difference mainly due to the unpolarized gluon PDF at low scales
  - Smaller degree of polarization than for quarks and antiquarks

Linear gluon polarization



- *Max scenario* starting from GJR distributions
- Double linear gluon polarization rapidly suppressed by evolution
  - even in most positive scenario

Linear gluon polarization



- *Max scenario* starting from GJR distributions
- Double linear gluon polarization rapidly suppressed by evolution
  - even in most positive scenario

Double ccbar production

- Promising for separation of DPS from SPS
  - Dominated by DPS — Hameren, Maciula, Szczurek, 2014
  - Studied in a series of papers — Gaunt, Hameren, Luszczak, Maciula, Szczurek
- Measured by LHCb (D0D0)
- Polarization (or any other quantum number interferences) has not been taken into account
- Focus on polarization
- Pure gluon channel dominates
- Gluon polarization suppressed by evolution
  - low scale ⇨ little room for evolution

Double ccbar production

- Unpolarized

$$d\sigma_{(gg)(gg)} \sim \frac{(1-z_1)^2 + z_1^2 - 1/N_c^2}{(1-z_1)z_1}\left[(1-z_1^2)^2 + z_1^2 + 4z_1(1-z_1) + \mathcal{O}(\frac{m^2}{m_{T1}^2})\right]$$
$$\times \{1 \leftrightarrow 2\} \int d^2\boldsymbol{y} f_{gg}(x_1, x_2, \boldsymbol{y}) \bar{f}_{gg}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

$$m_{Ti}^2 = m^2 + p_{Ti}^2 \qquad m_{Ti}^2 = m^2 + p_{Ti}^2 << m^2 \qquad z_i = \frac{m^2 - \hat{t}_i}{\hat{s}_i}$$

- Longitudinally polarized contribution

$$d\sigma_{(\Delta g \Delta g)(\Delta g \Delta g)} \sim \frac{(1-z_1)^2 + z_1^2 - 1/N_c^2}{(1-z_1)z_1}\left[(1-z_1^2)^2 + z_1^2 + 4z_1(1-z_1)\right]$$
$$\times \left(1 - 2\frac{m^2}{m_{T1}^2}\right)\{1 \leftrightarrow 2\} \int d^2\boldsymbol{y} f_{\Delta g \Delta g}(x_1, x_2, \boldsymbol{y}) \bar{f}_{\Delta g \Delta g}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

- Differences in hard scattering suppressed by m^2/m_{Ti}^2

Double ccbar production

- Mixed linear-unpolarized contribution

$$d\sigma_{(\delta gg)(g\delta g)} \sim \left((1-z_1)^2 + z_1^2 - 1/N_c^2\right) \frac{m^2}{m_{T1}^2} \left(1 - \frac{m^2}{m_{T1}^2}\right) \times \{1 \leftrightarrow 2\} \cos 2(\phi_1 - \phi_2) \int d^2\boldsymbol{y}\, \boldsymbol{y}^4 M^4 f_{\delta gg}(x_1, x_2, \boldsymbol{y}) \bar{f}_{g\delta g}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

  - Suppressed by m^2/m_{Ti}^2 in each hard part (due to helicity flip)

- Doubly linearly polarized contribution

$$d\sigma_{(\delta g\delta g)(\delta g\delta g)} \sim \left((1-z_1)^2 + z_1^2 - 1/N_c^2\right) \frac{(m^2 - m_{T1}^2)^2}{m_{T1}^4} \times \{1 \leftrightarrow 2\} \left(\cos 4(\phi_1 - \phi_2) + \mathcal{O}\left(\frac{m^8}{p_{T1}^4 p_{T2}^4}\right)\right) \times \int d^2\boldsymbol{y}\, f_{\delta g\delta g}(x_1, x_2, \boldsymbol{y}) \bar{f}_{\delta g\delta g}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

  - Less suppression in hard, but more from evolution of distributions

Double ccbar production

- In order to do numerics we need input for the DPDs
- For unpolarized we take

$$f_{gg}(x_1, x_2, \boldsymbol{y}; Q_0) = f_g(x_1, Q_0) f_g(x_2; Q_0) G(\boldsymbol{y}).$$

  - GJR2008lo for PDFs

Glück, Jimenez-Delgado, Reya, 2007

- For polarized we saturate the positivity bounds on polarized distributions, for example

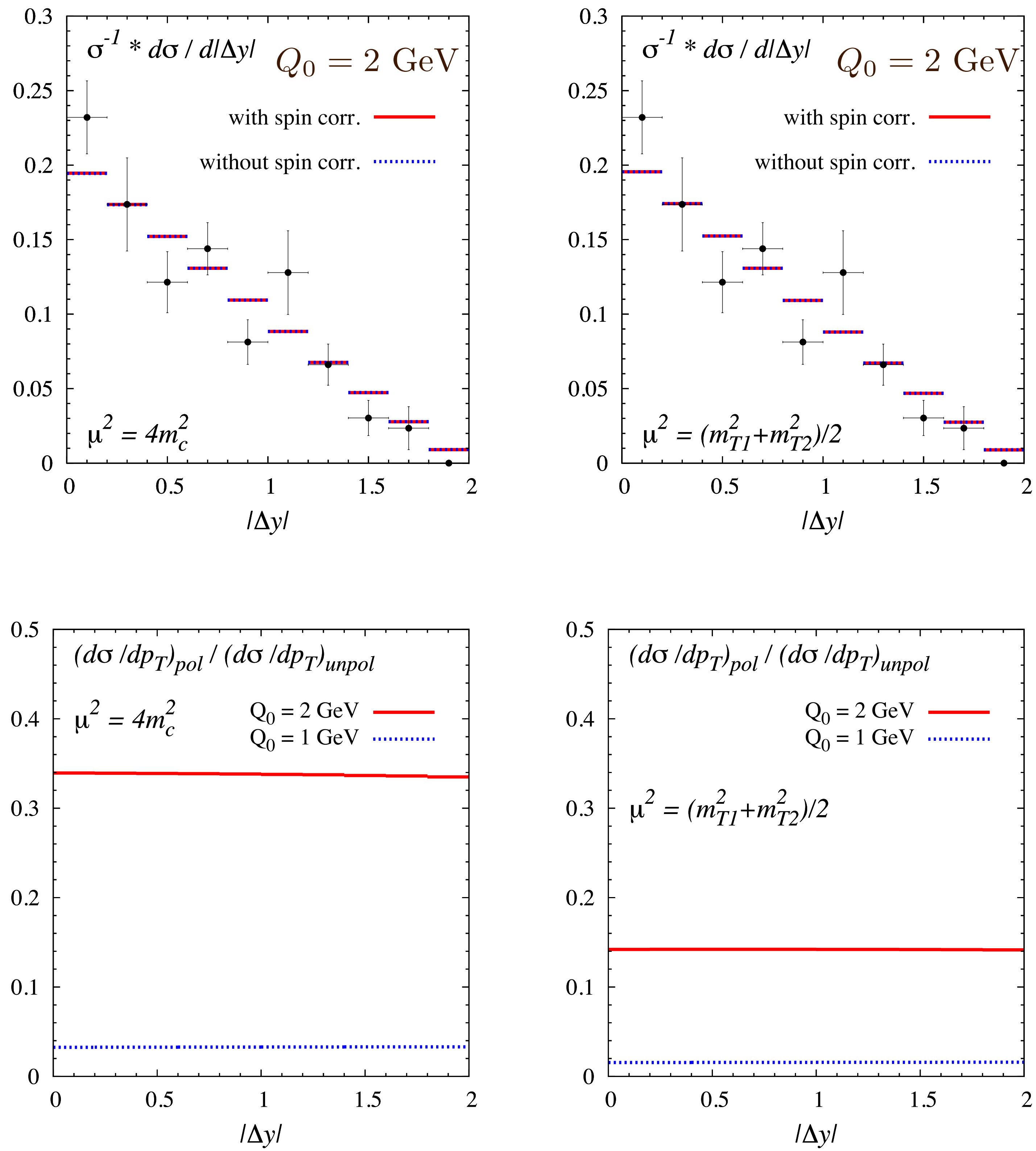
M. Diehl, TK, 2013

$$f_{\Delta g \Delta g}(x_1, x_2, \boldsymbol{y}; Q_0) = f_{gg}(x_1, x_2, \boldsymbol{y}; Q_0)$$

- Cuts: $3 \text{ GeV} \leq |p_{Ti}| \leq 12 \text{ GeV} \quad 2 \text{ GeV} \leq |y_i| \leq 4$
- Evolve DPDs with double DGLAP evolution
  - Polarized splitting kernels for polarized distributions
- Results for two choices of initial scales (and two choices for the hard scale in the DPDs)

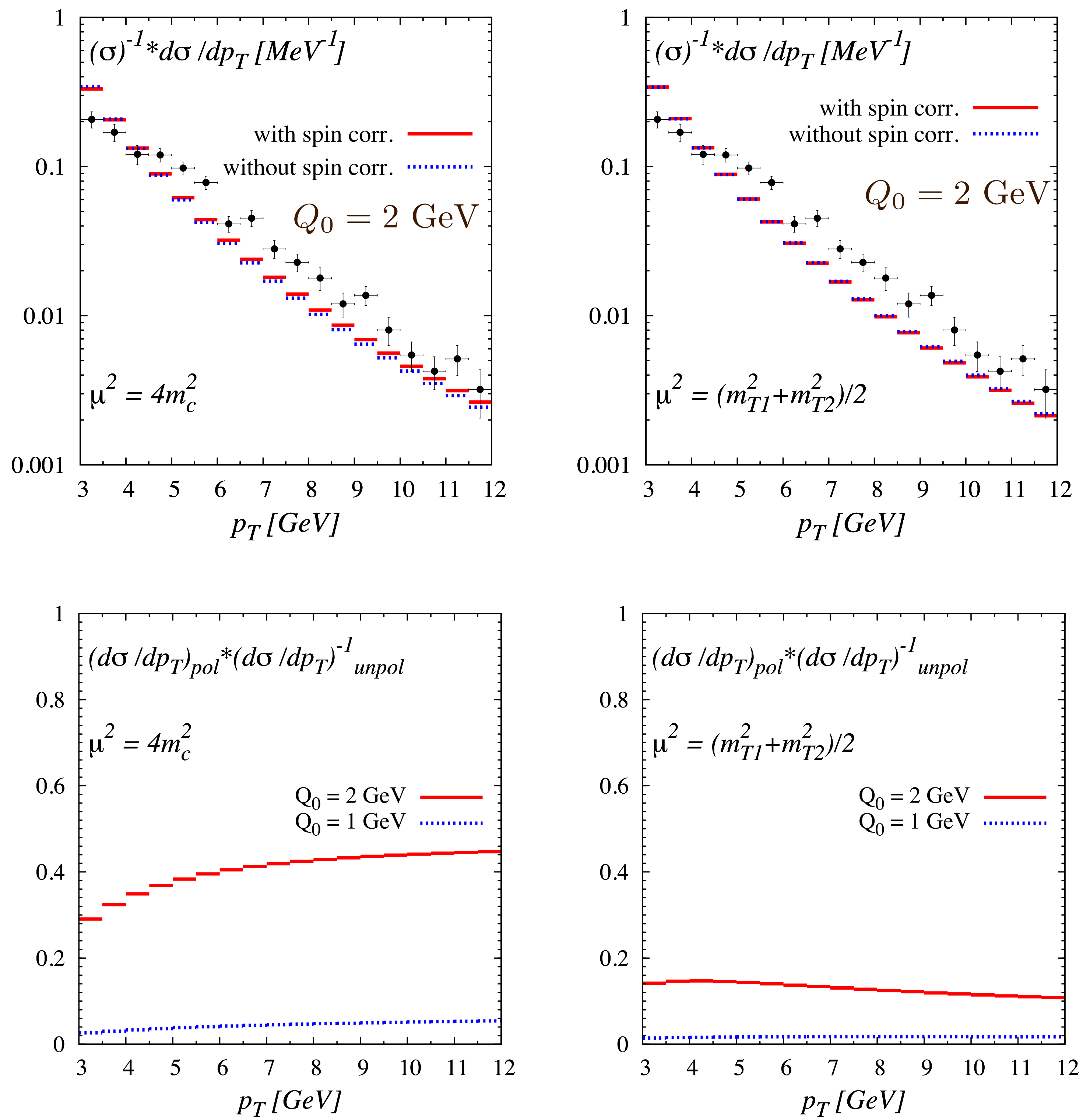
Cross section vs rapidity difference

- $D^0 D^0$ data from LHCb
- Polarization does not affect shape of distribution
- With $Q_0 = 1$ GeV small contribution of polarized gluons
- With $Q_0 = 2$ GeV large contribution of polarized gluons
- Strong dependence on scale choice



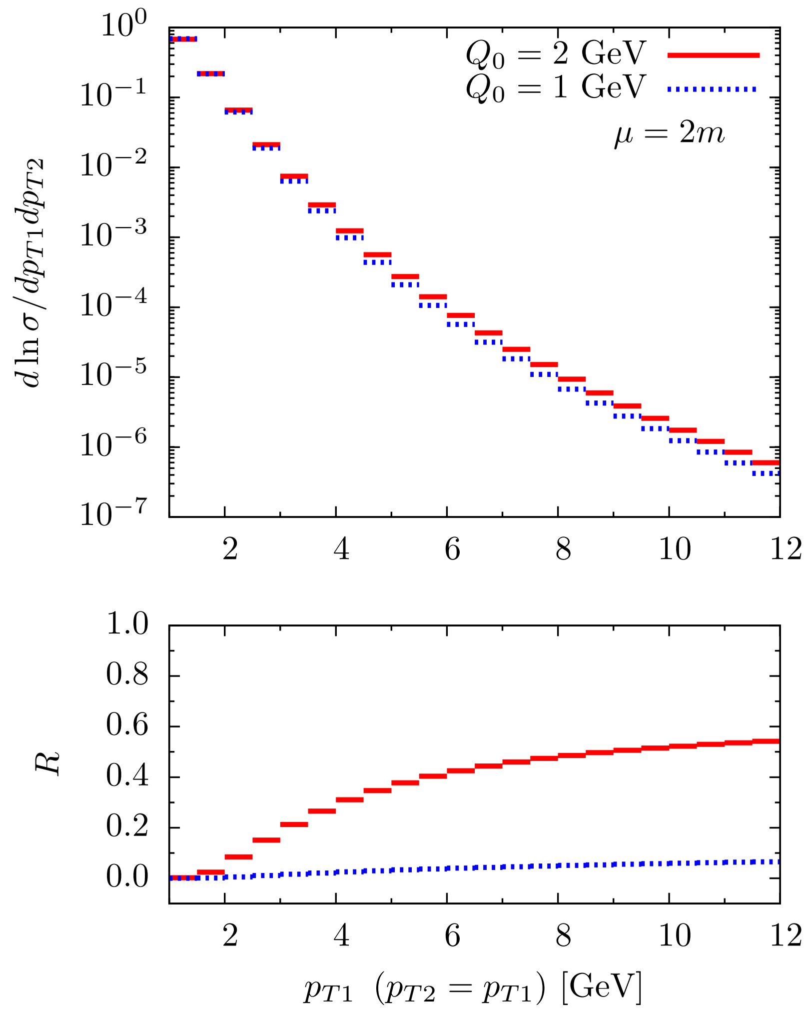
Cross section vs transverse momentum

- $D^0 D^0$ data from LHCb
- Polarization does not affect shape of distribution
- With $Q_0 = 1$ GeV small contribution of polarized gluons
- With $Q_0 = 2$ GeV large contribution of polarized gluons
- Strong dependence on scale choice



Polarization in double ccbar summary

- Size of polarization has strong dependence on input scale
  - With $Q_0 = 1$ GeV , get polarization effects of a few percent
  - With $Q_0 = 2$ GeV, get polarization effects of up to 50%
- Significant longitudinal polarization can be there in the data,
  - Difficult to disentangle
  - Other variables, more differential?
- Linearly polarized gluons gives dependence on azimuthal angles
  - The effect of linearly polarized gluons is small



Summary

- We can do more than σ_{eff}
- DPS theory advances towards a full treatment in QCD
- Learning piece by piece - moving towards a DPS license

- Future (utopia or realistic scenario?) with DPDs and correlations measured from data

- Thoughts from experimentalists, how can theory help you go further?
- Thoughts from pA and AA, can DPS teach you anything or vice versa?
- Thoughts from quarkonia perspective, benefits from DPS - quarkonia interactions?