Interference DPDs and polarization in double ccbar

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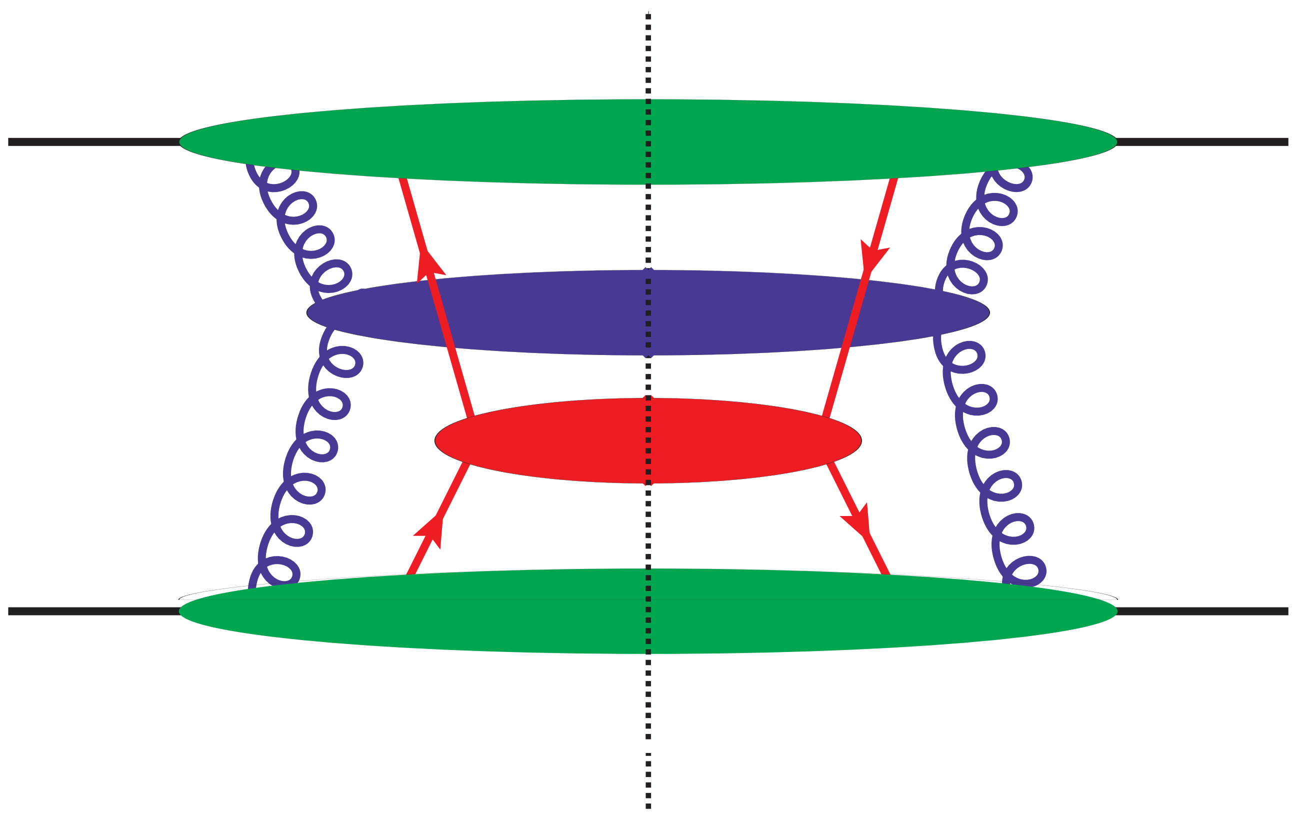


Based on arXiv: 1411.0726

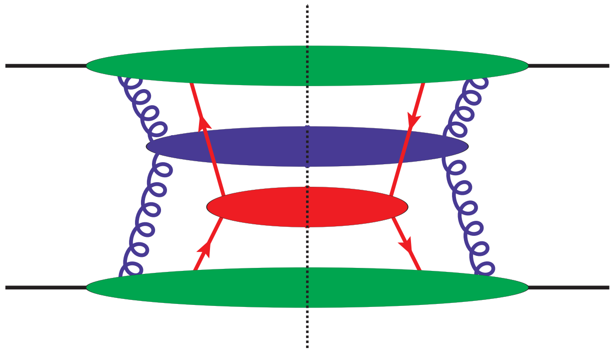
In collaboration with M.G. Echevarria, P.J. Mulders and C. Pisano

Krakow, 5th of November 2014

Outline

- Introduction to quantum correlations in DPS
- Discuss limits on interference double parton distributions (arXiv: 1411.0726)
- Discuss effects of polarization in double c-cbar production (work in progress)

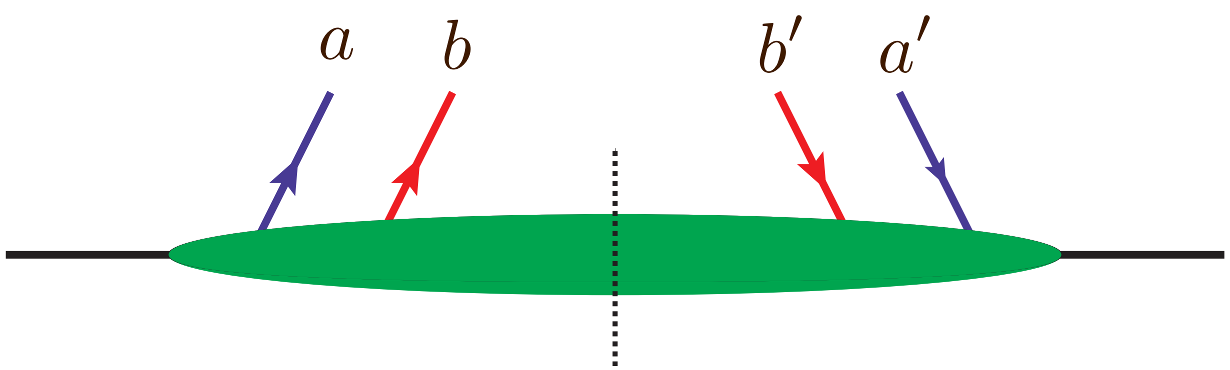
Interferences and correlations in DPS



- Schematic cross section

$$\frac{d\sigma_{DPS}}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2} = \frac{1}{C}\hat{\sigma}_1\hat{\sigma}_2 \int d^2\boldsymbol{y} F(x_1, x_2, \boldsymbol{y}) F(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

- Quantum numbers implicit
- DPS has richer structure than SPS
- Encoded in the double parton distributions



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

- Large number of DPDs - but not all are likely to be relevant
- Sizes of interference distributions unknown

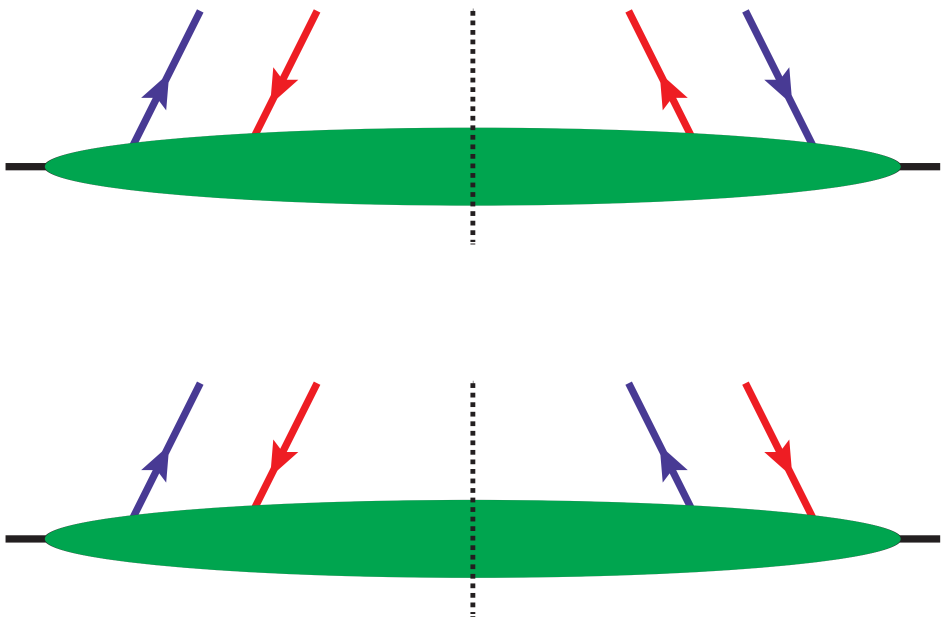
Correlations in DPS

- **Quantum number**
  - **Color**
  - **Fermion number**
  - **Flavor**
  - **Spin (polarization)**

1st part (Color, Fermion number, Flavor)

2nd part (Spin (polarization))

- Kinematical
  - Between x's
  - Between x's and $\boldsymbol{y}$
- Mixed
  - Parton type and $\boldsymbol{y}$
  - etc

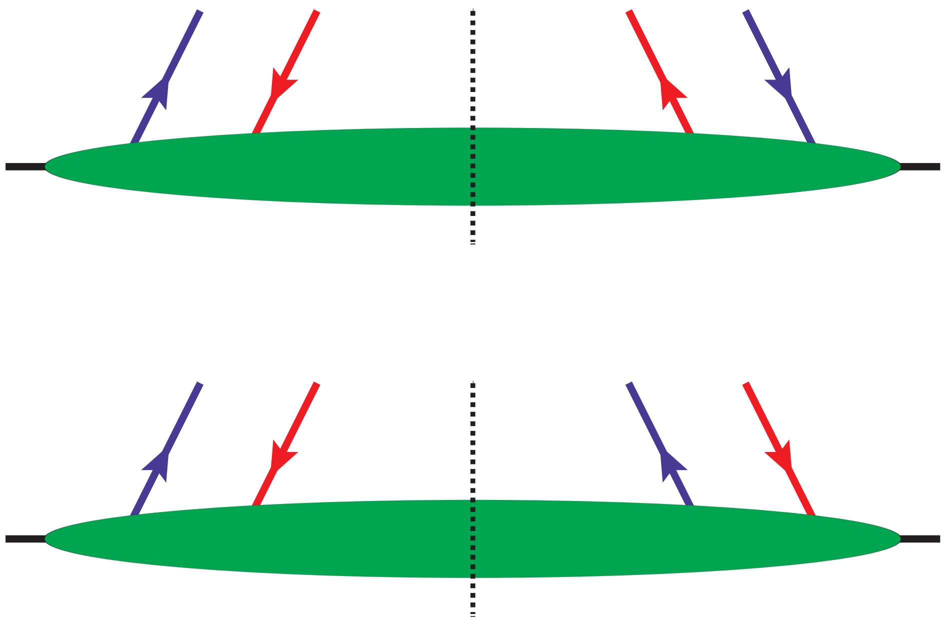


Correlations in DPS

- Quantum number
  - **Color**
  - **Fermion number**
  - **Flavor**

  } 1st part

  - **Spin (polarization)** } 2nd part



- DPDs studied in a number of different quark models
  - Correlations typically found to be sizable

H.-M. Chang, A.V. Manohar, W.J. Waalewijn, 2012;
M. Rinaldia S. Scopettaa M. Trainib V. Ventoc, 2014

- Have been included in cross section calculations of double vector boson production (photon, Z, W) A.V. Manohar, W.J. Waalewijn, 2012; TK, M. Diehl, 2012
- We will derive constrains on the sizes of the interference DPDs,

  $\Rightarrow$ Limiting correlation effects in DPS

Probability interpretation

- DPD - probability of finding two partons with momentum fraction x_1 and x_2 at transverse distance $\boldsymbol{y}$ (not true for interference distributions)
- Probability of finding the two partons in a general state gives

$$\sum_{\lambda_1'\lambda_2'\lambda_1\lambda_2} v^*_{\lambda_1'\lambda_2'}\,\rho_{(\lambda_1'\lambda_2')(\lambda_1\lambda_2)}\,v_{\lambda_1\lambda_2} \geq 0 \qquad \sum_{\lambda_1\lambda_2} |v_{\lambda_1\lambda_2}|^2 = 1$$

  - where λ_i 's are quantum numbers labeling the two partons (color, flavor, etc)

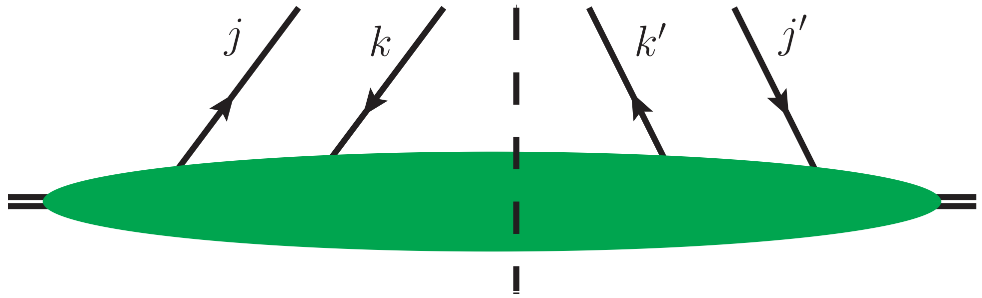
    $\Rightarrow$ Density matrix ρ is positive-semidefinite
- Organise DPDs in density matrices
- Eigenvalues are positive
  - Gives limits on the distributions
- Similar to bounds derived for polarized DPDs and single parton distributions

A. Bacchetta, M. Boglione, P.J. Mulders, 1999; M. Diehl, Ph. Hägler, 2005; M. Diehl, TK, 2013

Color in DPS

- Color in quark-antiquark DPD

$$F_{jj',kk'} \sim$$



- Decompose the color structure

$$3 \otimes \bar{3} = 1 \oplus 8$$

- t-channel - connect partons in amplitude with partner in conjugate

$$F_{jj',kk'} = \frac{1}{N_c^2}\left[{}^{1}F\ \delta_{jj'}\delta_{k'k} + \frac{2N_c}{\sqrt{N_c^2-1}}\, {}^{8}F\ t^a_{jj'} t^a_{k'k} \right]$$

Interference DPD

M. Diehl, D. Ostermeier, A. Schäfer, 2011

- Project out s-channel (connect partons in amplitude):

$$F^{(1)}_{q\bar{q}} = \frac{1}{N_c^2}\left({}^{1}F_{q\bar{q}} + \sqrt{N_c^2-1}\, {}^{8}F_{q\bar{q}} \right) \geq 0,$$

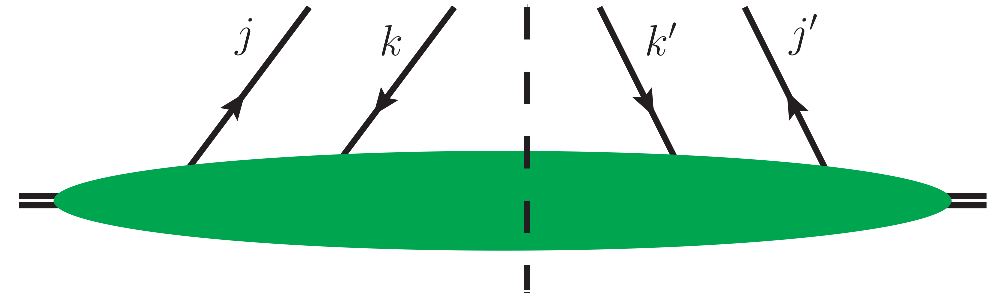
Probabilities

$$F^{(8)}_{q\bar{q}} = \frac{1}{N_c^2}\left({}^{1}F_{q\bar{q}} - \frac{1}{\sqrt{N_c^2-1}}\, {}^{8}F_{q\bar{q}} \right) \geq 0$$

Fermion-number and color in DPS

- Fermion number and color in quark-antiquark DPD

$$I_{q\bar{q}} \sim$$



- Decompose the color structure

$$3 \otimes \bar{3} = 1 \oplus 8$$

Interference DPDs

- t-channel

$$I_{jj',kk'} = \frac{1}{N_c^2}\left[{}^{1}I\, \delta_{jk'}\delta_{j'k} + \frac{2N_c}{\sqrt{N_c^2-1}}\, {}^{8}I\, t^a_{jk'} t^a_{j'k} \right]$$

M. Diehl, D. Ostermeier, A. Schäfer, 2011

- Project out s-channel (connect partons in amplitude):

$$I^{(1)}_{q\bar{q}} = \frac{1}{N_c^2}\left({}^{1}I_{q\bar{q}} + \sqrt{N_c^2-1}\, {}^{8}I_{q\bar{q}} \right),$$

NO probabilities

$$I^{(8)}_{q\bar{q}} = \frac{1}{N_c^2}\left({}^{1}I_{q\bar{q}} - \frac{1}{\sqrt{N_c^2-1}}\, {}^{8}I_{q\bar{q}} \right)$$

Constraining interference DPDs

- Construct color-fermion number density matrix

$$\begin{pmatrix} F_{q\bar{q}}^{(1)} & 0 & I_{\bar{q}q}^{(1)} & 0 \\ 0 & F_{q\bar{q}}^{(8)} & 0 & I_{\bar{q}q}^{(8)} \\ I_{q\bar{q}}^{(1)} & 0 & F_{\bar{q}q}^{(1)} & 0 \\ 0 & I_{q\bar{q}}^{(8)} & 0 & F_{\bar{q}q}^{(8)} \end{pmatrix}$$

- Columns (rows) correspond to color and fermion number states of the quark and antiquark in the (conjugate) amplitude
- Eigenvalues gives bounds on interference distributions

$$F_{q\bar{q}}^{(1)} + F_{\bar{q}q}^{(1)} \pm \sqrt{(F_{q\bar{q}}^{(1)} - F_{\bar{q}q}^{(1)})^2 + 4I_{q\bar{q}}^{(1)} I_{\bar{q}q}^{(1)}} \geq 0$$
$$F_{q\bar{q}}^{(8)} + F_{\bar{q}q}^{(8)} \pm \sqrt{(F_{q\bar{q}}^{(8)} - F_{\bar{q}q}^{(8)})^2 + 4I_{q\bar{q}}^{(8)} I_{\bar{q}q}^{(8)}} \geq 0$$

Constraining interference DPDs

- Translate the eigenvalues to bounds on the color and fermion number interference distributions

$$F^{(1)}_{q\bar{q}} + F^{(1)}_{\bar{q}q} \pm \sqrt{(F^{(1)}_{q\bar{q}} - F^{(1)}_{\bar{q}q})^2 + 4I^{(1)}_{q\bar{q}} I^{(1)}_{\bar{q}q}} \geq 0$$

$$F^{(8)}_{q\bar{q}} + F^{(8)}_{\bar{q}q} \pm \sqrt{(F^{(8)}_{q\bar{q}} - F^{(8)}_{\bar{q}q})^2 + 4I^{(8)}_{q\bar{q}} I^{(8)}_{\bar{q}q}} \geq 0$$

Interference DPDs

$$\begin{aligned} &{}^1F_{\bar{q}q} + {}^1F_{q\bar{q}} - \frac{{}^8F_{\bar{q}q} + {}^8F_{q\bar{q}}}{\sqrt{N_c^2 - 1}} \\ &\pm \sqrt{\left({}^1F_{\bar{q}q} - {}^1F_{q\bar{q}} + \frac{{}^8F_{q\bar{q}} - {}^8F_{\bar{q}q}}{\sqrt{N_c^2 - 1}}\right)^2 + 4\left({}^1I_{\bar{q}q} - \frac{{}^8I_{\bar{q}q}}{\sqrt{N_c^2 - 1}}\right)\left({}^1I_{q\bar{q}} - \frac{{}^8I_{q\bar{q}}}{\sqrt{N_c^2 - 1}}\right)} \geq 0, \end{aligned}$$

$$\begin{aligned} &{}^1F_{\bar{q}q} + {}^1F_{q\bar{q}} + \sqrt{N_c^2 - 1}({}^8F_{\bar{q}q} + {}^8F_{q\bar{q}}) \\ &\pm \sqrt{\left({}^1F_{\bar{q}q} - {}^1F_{q\bar{q}} + \sqrt{N_c^2 - 1}({}^8F_{\bar{q}q} - {}^8F_{q\bar{q}})\right)^2 + 4\left({}^1I_{\bar{q}q} + \sqrt{N_c^2 - 1}\,{}^8I_{\bar{q}q}\right)\left({}^1I_{q\bar{q}} + \sqrt{N_c^2 - 1}\,{}^8I_{q\bar{q}}\right)} \geq 0. \end{aligned}$$

Interference constraints summary

- Here we have derived limits on interference in color and fermion number of the quark-antiquark distributions
- Derived limits on:
    - Flavor interference DPDs
    - Color interference
    - Fermion-number interference
- For all parton types (quarks, antiquarks and gluon DPDs)
- Reduce the number of independent double gluon distributions by showing that ${}^{10}F_{gg} = {}^{\overline{10}}F_{gg}$

Interference constraints summary

- Set limits on the possible sizes of interference DPDs
- The density matrices and bounds can teach us about the DPDs and their interrelations
- Combined with evolution, the bounds greatly reduce the number of relevant DPDs in a given process
- Combined with previous limits on polarized DPDs

  $\Rightarrow$ Constraints on all types of quantum number interferences and correlations in DPS.

- Can aid in constructing models for DPDs
  (as we will see in the next part)

Double ccbar production

- Promising for separation of DPS from SPS
  - Dominated by DPS
  - Studied in a series of papers

See talks by J. Gaunt and R. Maciuła

- Measured by LHCb (D0D0 final state)
- Polarization (or any other quantum number interferences) has not been taken into account
- We focus on the effects of polarization
- Polarization suppressed by evolution, in particular in the gluon sector - but the low scales of ccbar production leaves only little room for evolution

Double ccbar production

- Pure gluon channel dominates

See talk by R. Maciuła

- DPS polarization in 2 times $gg \to c\bar{c}$
  - Gluons can be unpolarized (g), longitudinally polarized (Δg) and linearly polarized (δg)
- The nonzero cross section contributions are

$$d\sigma_{(gg)(gg)},\ d\sigma_{(\Delta g\Delta g)(\Delta g\Delta g)},\ d\sigma_{(\delta gg)(g\delta g)},\ d\sigma_{(\delta g\delta g)(\delta g\delta g)}$$

- Cuts as in the LHCb D0D0 measurement:

$$3\ \text{GeV} \leq |p_{Ti}| \leq 12\ \text{GeV} \qquad 2\ \text{GeV} \leq |y_i| \leq 4$$

LHCb Collaboration, 2012

  - For these cuts

$$m_{Ti}^2 = m^2 + p_{Ti}^2 \qquad m_{Ti}^2 = m^2 + p_{Ti}^2 << m^2$$

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

M. Glück, P. Jimenez-Delgado, E. Reya, 2007

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

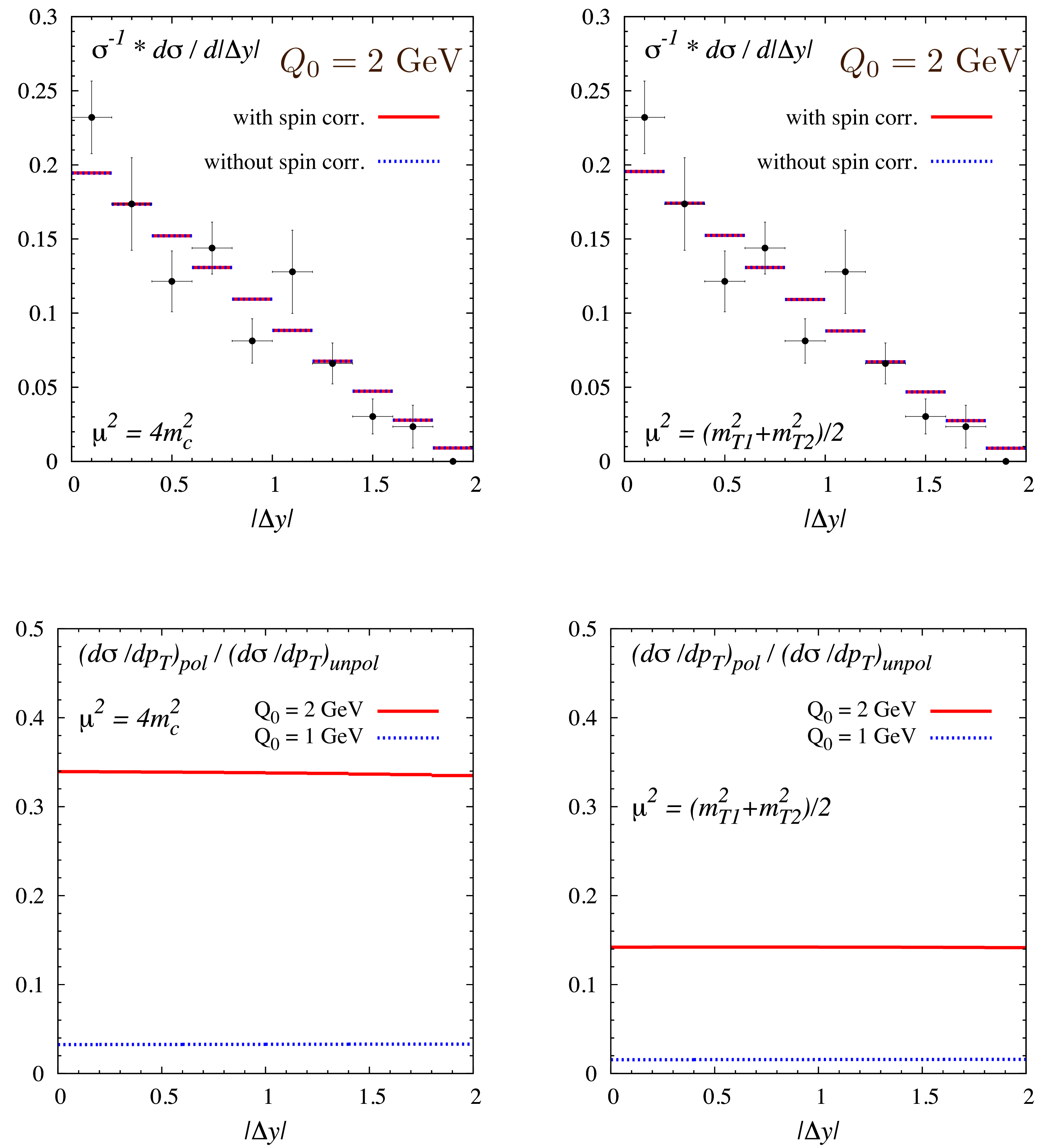
M. Diehl, TK, 2013

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

- Cuts: $3\ \text{GeV} \leq |p_{Ti}| \leq 12\ \text{GeV} \quad 2\ \text{GeV} \leq |y_i| \leq 4$
- Evolve up to higher scales with double DGLAP evolution
  - Polarized splitting kernels for polarized distributions
- We will show 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

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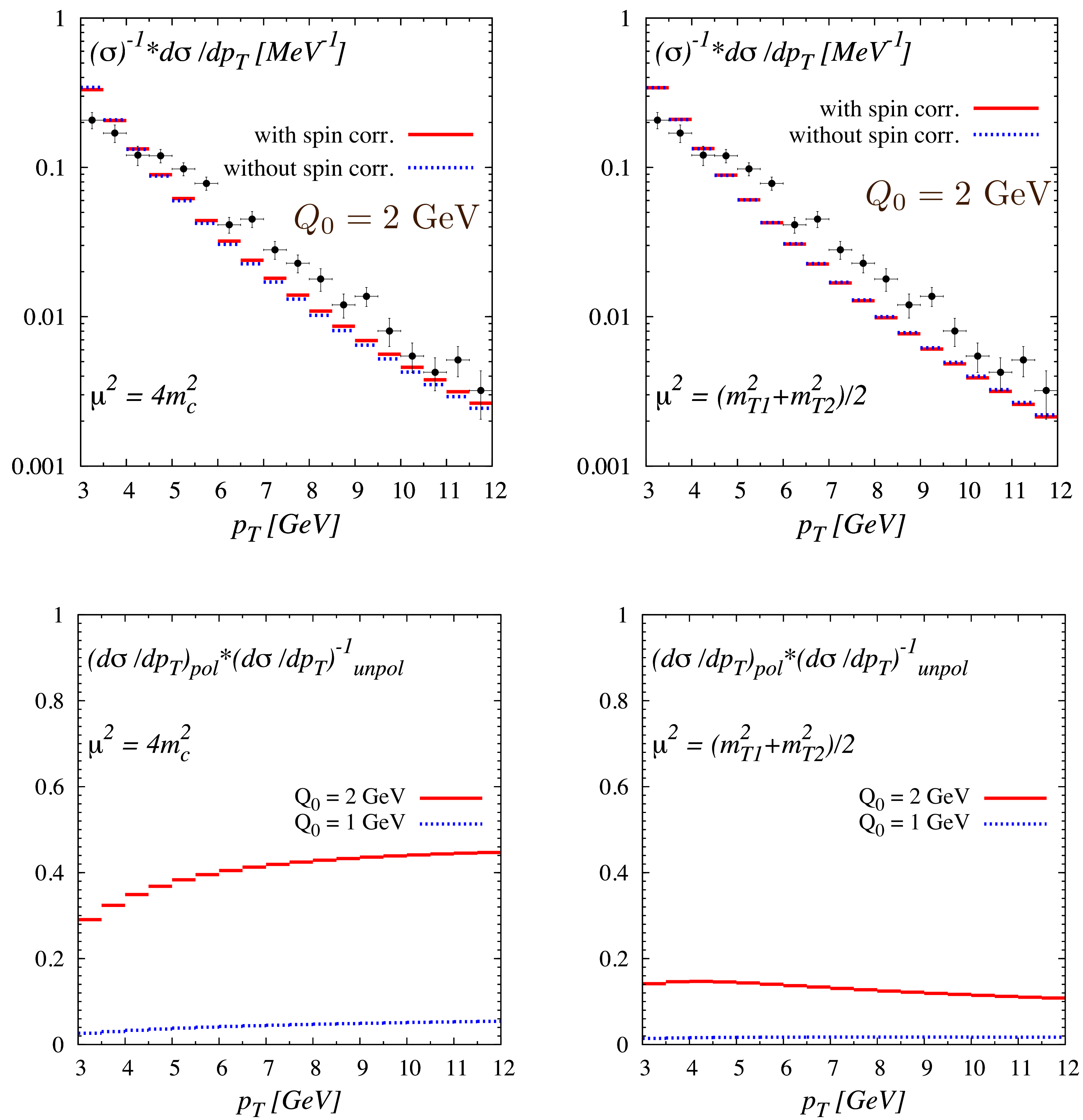

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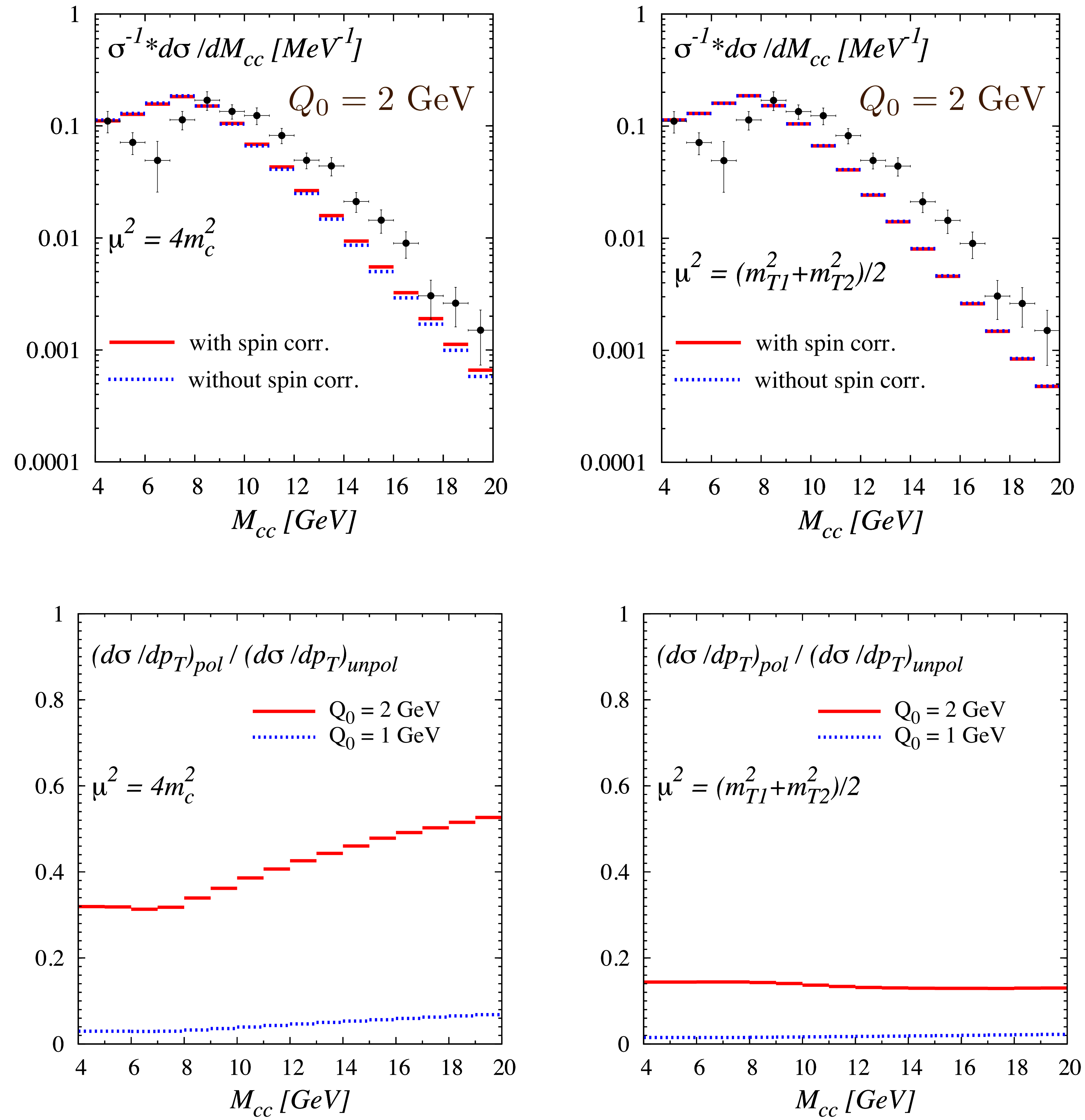

Polarization in double ccbar summary

- Size of polarization has very strong dependence on input scale
    - With $Q_0 = 1$ GeV, our input model gives polarization effects of a few percent
    - With $Q_0 = 2$ GeV, our input model gives polarization effects of up to 50%
- Cannot draw any strong conclusion about the effect of polarization
- Significant longitudinal polarization might be there in the experimental data, but the effect (overall size of the cross section) makes it difficult to disentangle
- Linearly polarized gluons gives dependence on azimuthal angles
    - The effect of linearly polarized gluons is small

Outlook

- Finalize numerics for linearly polarized gluons
- Explore momentum regions where the shape differences can be larger
  - For example, lower transverse momentum
- Puzzle of the $\cos(2\Delta\phi)$ modulation of D0D0 observed by LHCb:
  - $d\sigma_{(g\delta g)(\delta gg)}$ gives the correct modulation, but too small amplitude
  - Small effect due to helicity flip of gluon
  - Suppression expected to be lifted if gluon has transverse momentum
  - NLO corrections are large - as discussed in the talk by R. Maciuła
  - Can lift the suppression in the hard cross section
  - Can get sizable contribution from 1v2, 2v1 (as discussed by J. Gaunt) which can enhance spin correlations

  $\Rightarrow$ More work to be done!