SABRINA COTOGNO

VRIJE UNIVERSITEIT (VU) AND NIKHEF, AMSTERDAM

In collaboration with Tomas Kasemets (Johannes Gutenberg University, Mainz)

and Miroslav Myska (Czech Technical University, Prague)

SPIN AND KINEMATIC CORRELATIONS BETWEEN PARTONS INSIDE THE PROTON

SPIN2018 - 10-14 September, Ferrara

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PART I

INTERPARTON CORRELATIONS

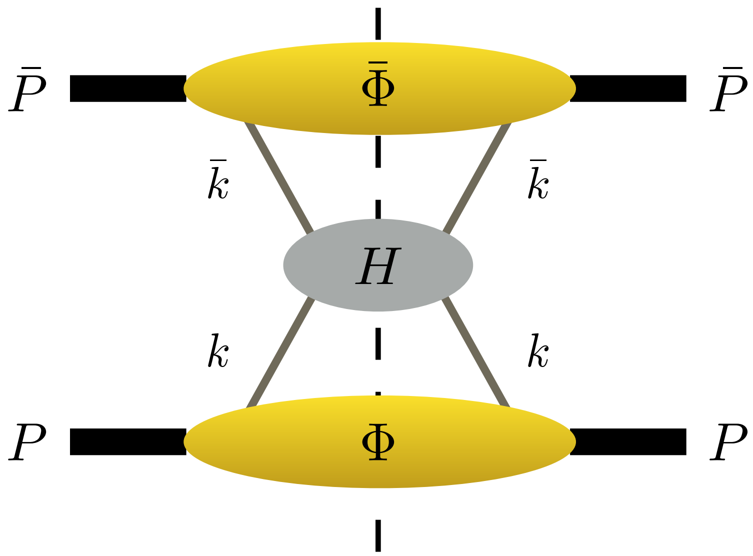
The two-parton information of the proton structure is contained in the double parton correlator

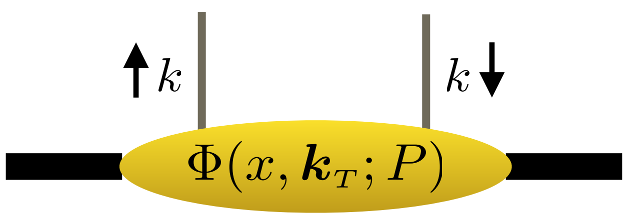
Analogously to the TMD case, we define the relevant correlator that contains such nonperturbative information

We start from what we are all familiar with:

FACTORIZED FORMULA FOR SINGLE PARTON SCATTERING (DRELL-YAN)

$$\frac{d\sigma}{dx\,d\bar{x}\,d\boldsymbol{q}_T} \sim \int d^2\boldsymbol{k}_T d^2\bar{\boldsymbol{k}}_T \delta^{(2)}(\boldsymbol{k}_T + \bar{\boldsymbol{k}}_T - \boldsymbol{q}_T) H(q^2) \Phi(x, \boldsymbol{k}_T; P) \bar{\Phi}(\bar{x}, \bar{\boldsymbol{k}}_T, \bar{P})$$





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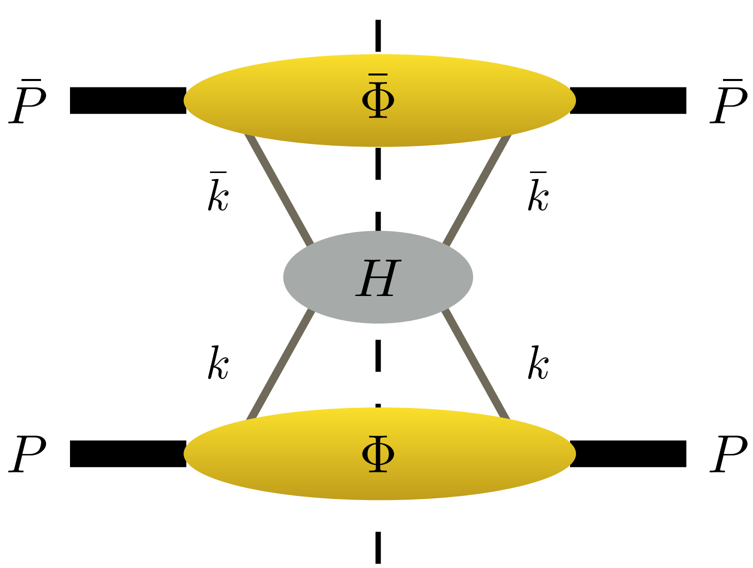
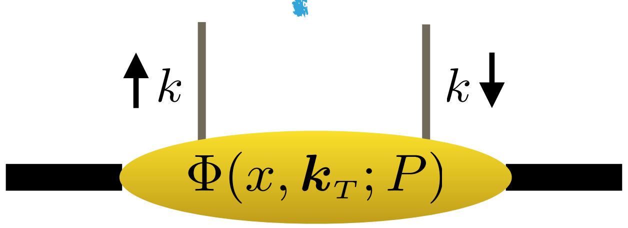


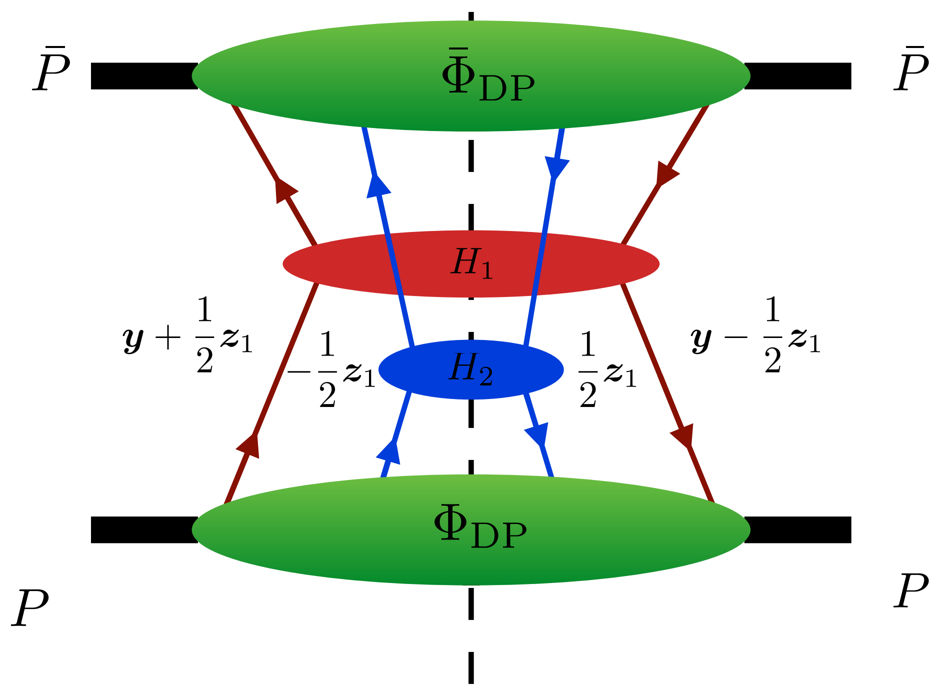


Contains all info on the 3D structure in momentum space, including the quantum structure (color, spin,flavor)

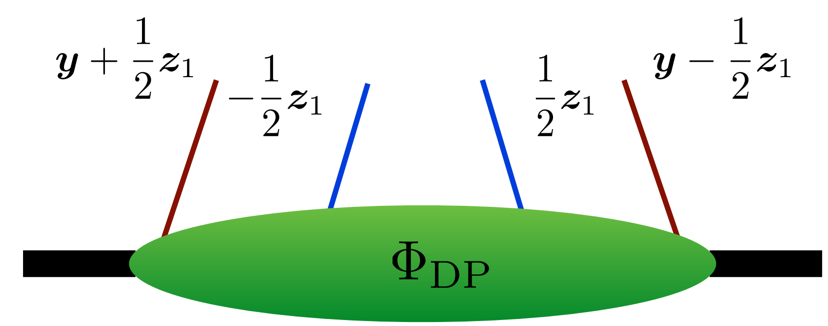
Complete parton-proton spin correlations in 3D momentum space

THE PROTON STRUCTURE THROUGH A (PARTON-)PAIR OF GLASSES

The relevant object is the double parton (DP) correlator

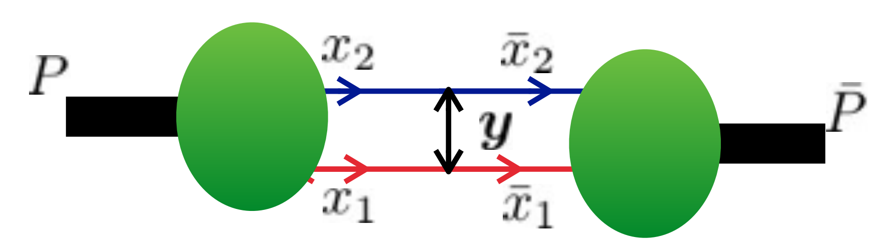


Paver, Treleani (1982); Mekhfi (1985)
Diehl, Ostermeier, Schäfer, (2011)



$$\frac{d\sigma_{DP}}{\prod_{i=1}^{2} dx_i d\bar{x}_i d^2\boldsymbol{q}_{Ti}} \sim \prod_{i=1}^{2} \int d^2\boldsymbol{z}_{T_i} d^2\boldsymbol{y} e^{-i\boldsymbol{q}_{T1}\cdot\boldsymbol{z}_{T1}-i\boldsymbol{q}_{T2}\cdot\boldsymbol{z}_{T2}} H_i(q_i^2)\Phi_{DP}(x_i,\boldsymbol{z}_{Ti},\boldsymbol{y})\bar{\Phi}_{DP}(\bar{x}_i,\bar{\boldsymbol{z}}_{Ti},\boldsymbol{y})$$

It “doubles” all the complications and includes INTERPARTON correlations



TYPE OF CORRELATIONS BETWEEN PARTONS INSIDE THE PROTON

Simplifications: neglect transverse momenta of the partons, consider unpolarized proton

$$\frac{d\sigma_{DP}}{\prod_{i=1}^{2} dx_i d\bar{x}_i} \sim \prod_{i=1}^{2} \int d^2\boldsymbol{y} H_i(q_i^2) \Phi_{DP}(x_i, \boldsymbol{y}) \bar{\Phi}_{DP}(\bar{x}_i, \boldsymbol{y})$$

The correlator describes quantum correlations, kinematical or mixed ones:

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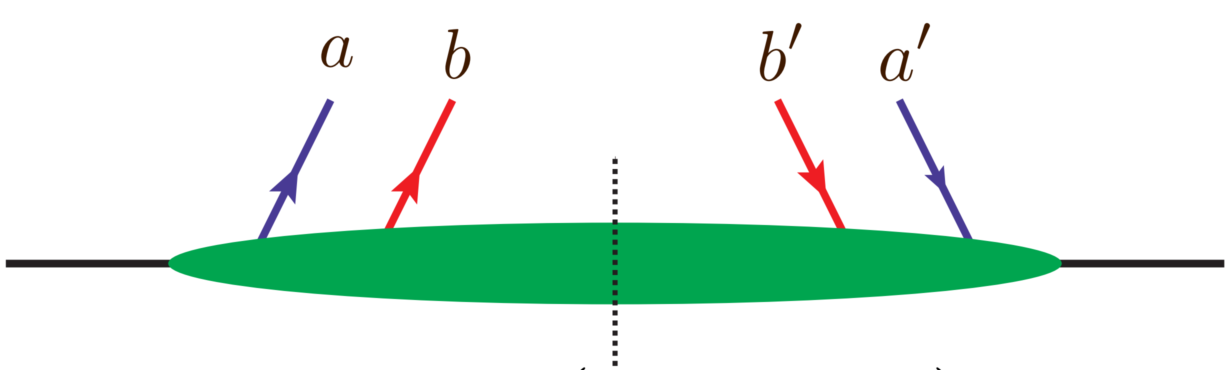
The correlator describes quantum correlations, kinematical or mixed ones:

- Color
- Fermion number interference
- Spin (polarization)
  - longitudinal
- Flavor interference



$$\Phi_{DP}(x_1, x_2, \boldsymbol{y})$$

- Between $\boldsymbol{y}$ and x_i
- Parton type and $\boldsymbol{y}$
- Between x_i
- ...

Mehkfi, Artru (1985)
Diehl, Ostermeier, Schäfer, (2011)
Manohar, Waalewijn (2012)
Echevarria,Kasemets,Mulders,Pisano, (2014)
Rinaldi, Scopetta, Traini, Vento (2014)
Kasemets, Scopetta (2017)

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

SPIN STRUCTURE

The DP correlator contains polarized distributions also in the case of unpolarized parent hadron (similar to TMD $\longrightarrow$ access parton spin)

One can parametrize the Φ_{DP} in terms of double parton distributions DPDs that contain parton polarization information.

$$F_{q_1,q_2} \sim \langle P|(\bar{q}_1\Gamma_{q_1}q_1)(\bar{q}_2\Gamma_{q_2}q_2)|P\rangle$$

The different Dirac matrices select quarks of different polarization:

$$\Gamma_q = \frac{1}{2}\gamma^+ \qquad \Gamma_{\Delta q} = \frac{1}{2}\gamma^+\gamma_5 \qquad \Gamma^j_{\delta q} = \frac{1}{2}i\sigma^{j+}\gamma_5 \quad (j = 1, 2)$$

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Unpolarized

$$f_{q_1q_2}(x_1, x_2, \boldsymbol{y})$$

Longitudinally polarized

$$f_{\Delta q_1\Delta q_2}(x_1, x_2, \boldsymbol{y})$$

Transversely polarized

$$f_{\delta q_1\delta q_2}(x_1, x_2, \boldsymbol{y})$$

Mixed

$$f_{q_1\delta q_2}(x_1, x_2, \boldsymbol{y})$$

PART II

MODEL OF DOUBLE PARTON DISTRIBUTIONS AND CORRELATIONS

SIMPLE MODEL FOR THE DOUBLE PARTON DISTRIBUTION

Simplest possible approach is to assume that there are NO correlations of any type between the two partons inside the proton.

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

W+2j measurement, ATLAS Collaboration 2013
W+2j measurement, CMS Collaboration 2013
4 j measurement, ATLAS Thesis 2013

Simple and practically useful but theoretically insufficient
Correlations can be important!
All the DPDs are unknown, therefore we need to reduce them to single parton distributions.

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All the DPDs are unknown, therefore we need to reduce them to single parton distributions.

We assume that (unpolarized distribution):

$$f(x_1, x_2, \boldsymbol{y}; Q_0) = f(x_1; Q_0) f(x_2; Q_0) G(\boldsymbol{y})$$

$$\int d^2\boldsymbol{y} G^2(\boldsymbol{y}) = \sigma_{eff}^{-1}$$

Valid at a low initial scale (1 GeV). Evolution with doubleDGLAP always creates correlations.

INCLUSION OF SPIN

We use positivity bounds to model the polarized distributions

The collinear DP correlator is a diagonal operator. Some combination of functions have probability interpretations.

$$|f_{\Delta q \Delta q}| \leq f_{qq}$$

POLARIZATION SCENARIO

Diehl, Kasemets (2012)

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

We saturate the bound at the initial (low) scale and then evolve up to the W boson mass scale with polarized dDGLAP

MIX-TO-MAX POLARIZATION SCENARIO

$$f_{\Delta q \Delta q}(x_1, x_2, \boldsymbol{y}; Q_0) = (-1)^n f_{qq}(x_1, x_2, \boldsymbol{y}; Q_0)$$

$n = 1$ both quarks or antiquarks in the pair
$n = 2$ mixed quark-antiquark in the pair

We saturate the bound with mixed signs at the initial (low) scale and then proceed with polarized dDGLAP

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We saturate the bound with mixed signs at the initial (low) scale and then proceed with polarized dDGLAP

- Insensitiveness of the results from a change of the initial low scale (from 1 GeV to 2 GeV).
- Within what is allowed by the positivity bounds, we try to maximize the effects of polarization (mix-to-max scenario has the biggest impact on the final state distributions of all the other correlations we have investigated).
- Maximizing the correlation scenarios will help estimate if/when experiments can start detecting or constraining these correlation models.

PART III

IMPACT OF QUARK POLARIZATION IN SAME-SIGN W BOSON PAIR PRODUCTION (SSW)

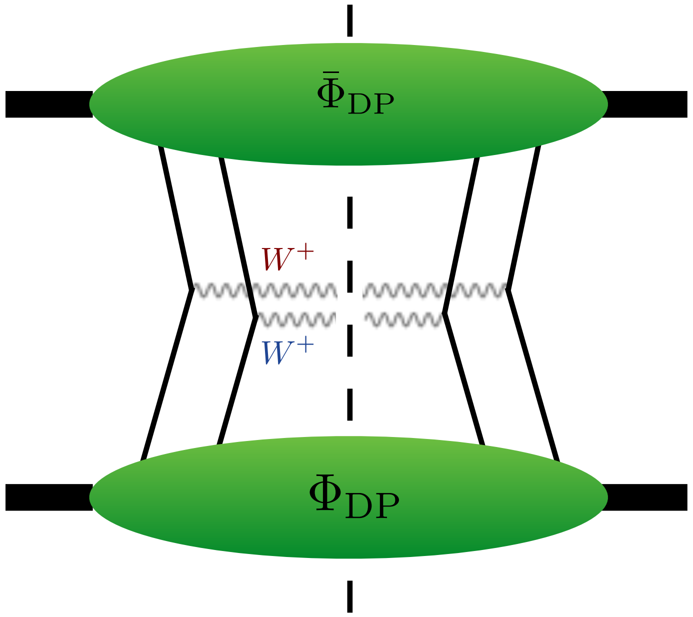
HOW MUCH IMPACT CAN THE SPIN OF THE PARTONS HAVE?

It's hard to tell in general, we focus on a process:

Production of W boson pair with the same electric charge (SSW)

Gaunt et al (2010)

CMS collaboration (2017)



- It is initiated by quarks (we can study quark polarization)
- The W couples only with left-handed (right-handed) quarks (antiquarks) -> helicity flip is not allowed -> only longitudinal polarization of the quarks is directly accessed (no double transversity)

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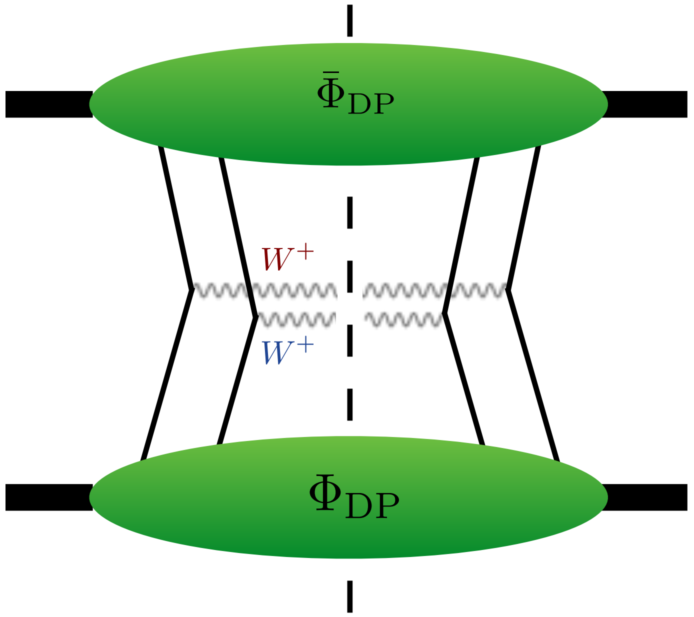
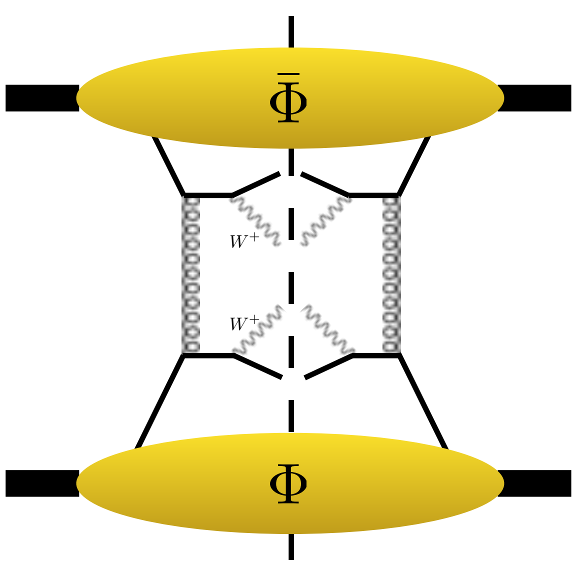


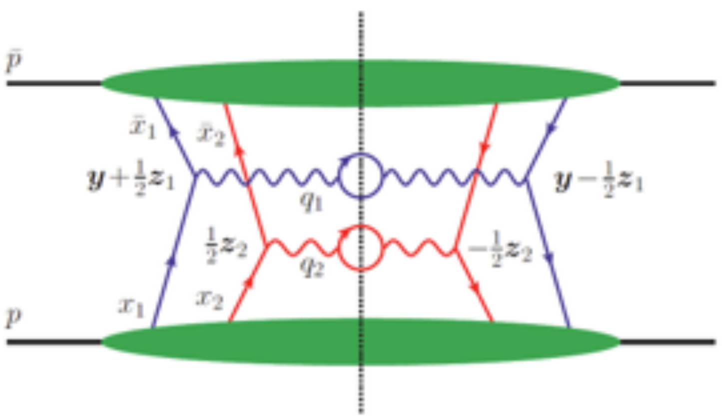


- It is initiated by quarks (we can study quark polarization)
- The W couples only with left-handed (right-handed) quarks (antiquarks) -> helicity flip is not allowed -> only longitudinal polarization of the quarks is directly accessed (no double transversity)
- The single parton equivalent is suppressed and it involves the production of two jets. This makes the DPS process very clean (more later if time left).

IMPACT OF POLARIZATION IN THE CROSS SECTION

Considering quark polarization, the expression for the cross section reads:

Kasemets (2013)



$$
\begin{aligned}
\sim\; & (1-\tanh\eta_{\mu_1})^2(1-\tanh\eta_{\mu_2})^2 \int d^2\boldsymbol{y}\,(f_{q_1q_2} + f_{\Delta q_1\Delta q_2})(\bar{f}_{\bar{q}_3\bar{q}_4} + \bar{f}_{\Delta\bar{q}_3\Delta\bar{q}_4}) \\
& (1-\tanh\eta_{\mu_1})^2(1+\tanh\eta_{\mu_2})^2 \int d^2\boldsymbol{y}\,(f_{q_1\bar{q}_4} - f_{\Delta q_1\Delta\bar{q}_4})(\bar{f}_{\bar{q}_3q_2} - \bar{f}_{\Delta\bar{q}_3\Delta q_2}) \\
& (1+\tanh\eta_{\mu_1})^2(1-\tanh\eta_{\mu_2})^2 \int d^2\boldsymbol{y}\,(f_{\bar{q}_3q_2} - f_{\Delta\bar{q}_3\Delta q_2})(\bar{f}_{q_1\bar{q}_4} - \bar{f}_{\Delta q_1\Delta\bar{q}_4}) \\
& (1+\tanh\eta_{\mu_1})^2(1+\tanh\eta_{\mu_2})^2 \int d^2\boldsymbol{y}\,(f_{\bar{q}_3\bar{q}_4} + f_{\Delta\bar{q}_3\Delta\bar{q}_4})(\bar{f}_{q_1q_2} + \bar{f}_{\Delta q_1\Delta q_2})
\end{aligned}
$$

Longitudinal polarization

$\eta_\mu \rightarrow$ muon pseudorapidity

Longitudinal polarization changes both the **size** and the **shape** of the cross section.

OUR “GOLDEN” OBSERVABLE - ASYMMETRY

$$\sigma^-$$

Muons in opposite hemisphere of the detector

$$A = \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}$$

$$\sigma^+$$

Muons in the same hemisphere of the detector

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$$A = \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}$$

σ^+

Muons in the same hemisphere of the detector

Great observable from the theoretical point of view

$A = 0$

In the uncorrelated scenario the asymmetry must always be zero

$A \neq 0$

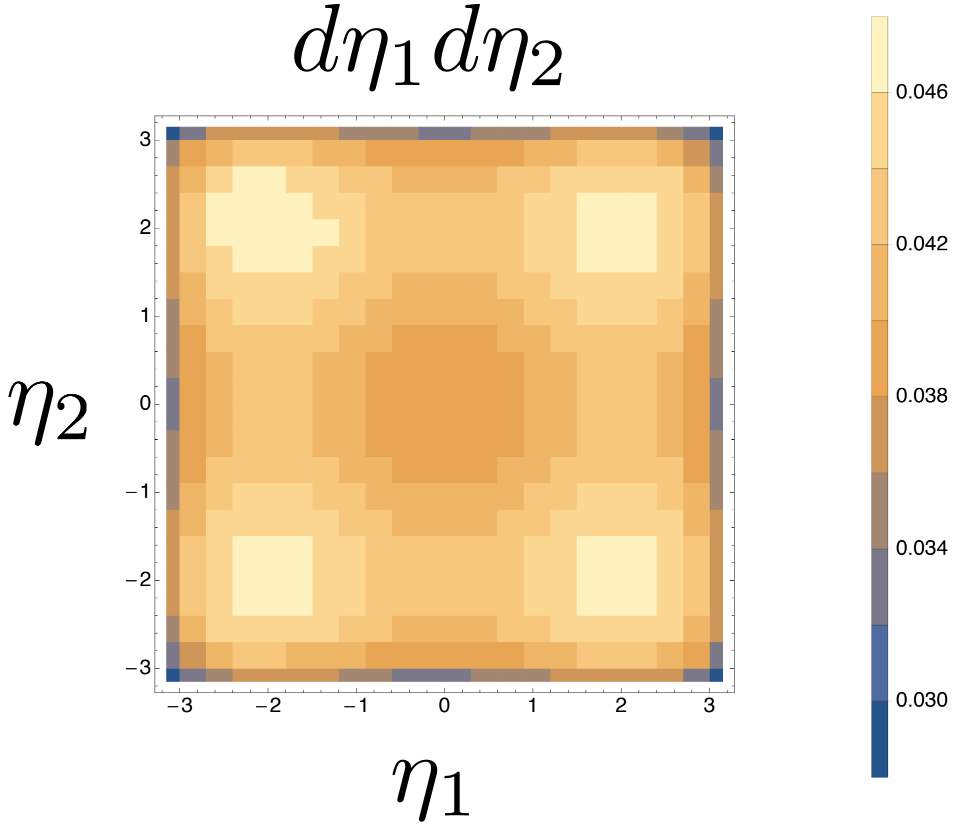
A value different from zero is a sign of parton correlation

INTERMEZZO – COMMENTS

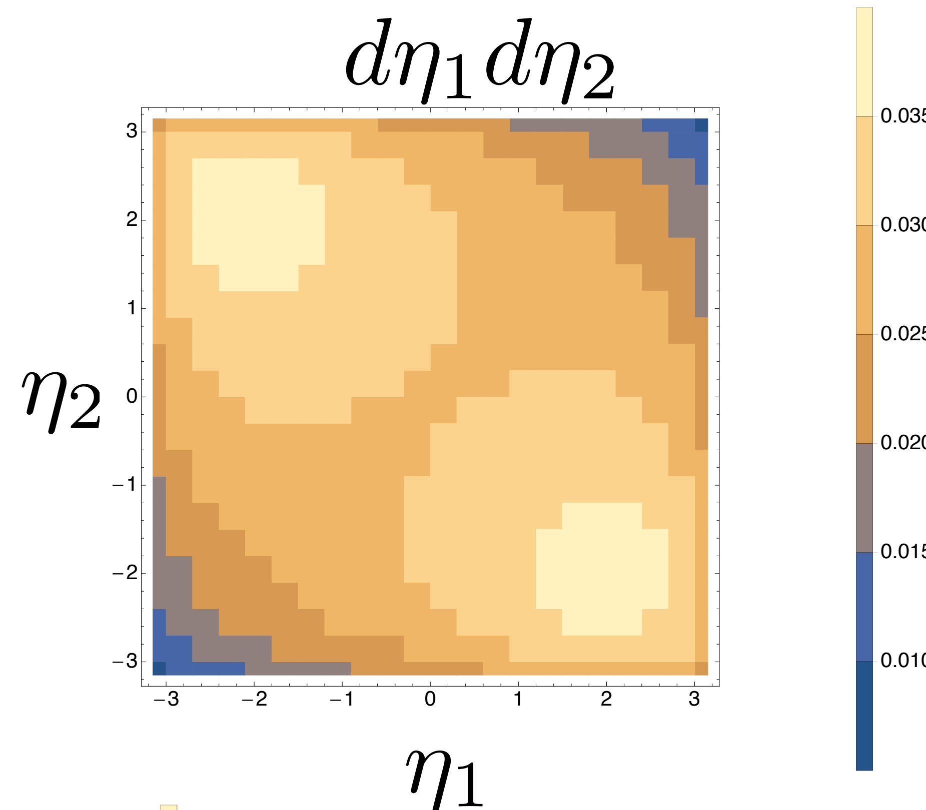
- How big/small the DPDs are is unknown (the measurements are affected by the extraction of σ_{eff}), so we need to search for a relative change in specific observables.
- Including polarization in different models can change the cross section up to 30%
- Ranging between the several correlation scenarios (quantum and kinematic) the mix-to-max polarization scenario produces the largest asymmetry.

	Unp	Pol	Mix-Pol
A	0.00	-0.05	0.12
σ [fb]	1.74	1.90	1.21

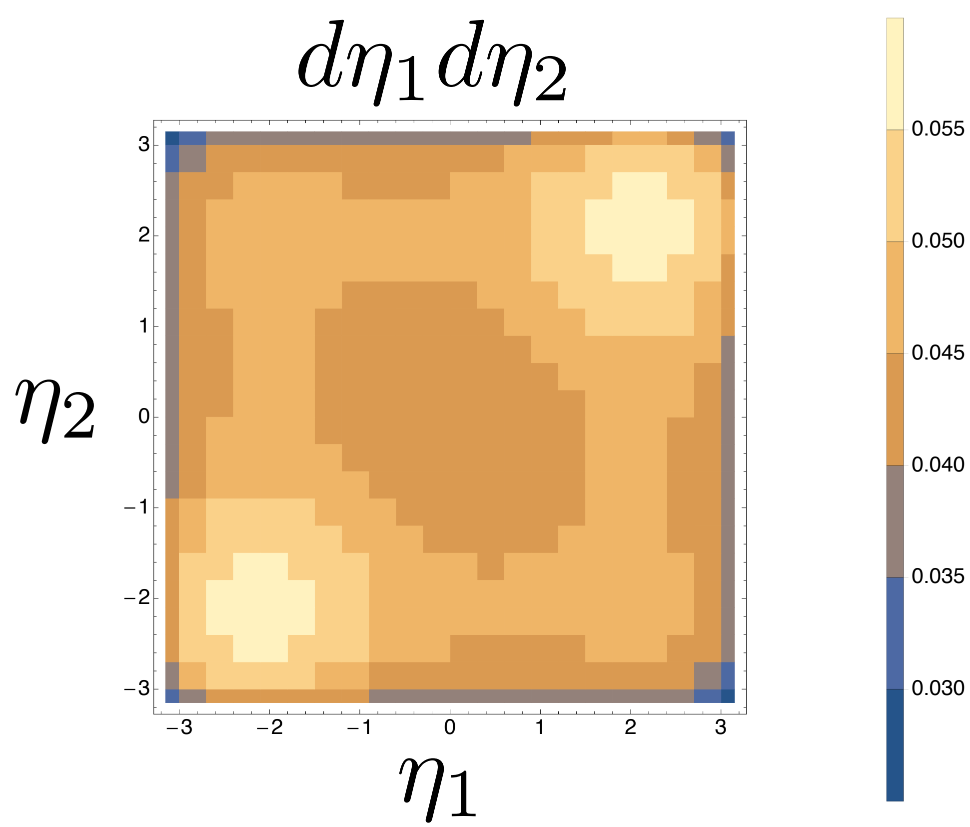
$$\left.\frac{d\sigma_{WW}\right|_{\text{Unp}}}{d\eta_1 d\eta_2}$$



$$\left.\frac{d\sigma_{WW}\right|_{\text{Mix-Pol}}}{d\eta_1 d\eta_2}$$



$$\left.\frac{d\sigma_{WW}\right|_{\text{Pol}}}{d\eta_1 d\eta_2}$$



Symmetric in the unpolarized scenario…

Distorted distribution in polarized cases!

ACCOUNTING FOR INITIAL STATE RADIATIONS AND ALL THAT…

- Herwig 7 is used to generate final-state distributions starting from our correlated parton level results.
- The default Herwig is re-weighted (more details in the upcoming paper by Cotogno, Kasemets, Myska 1809.xxx)

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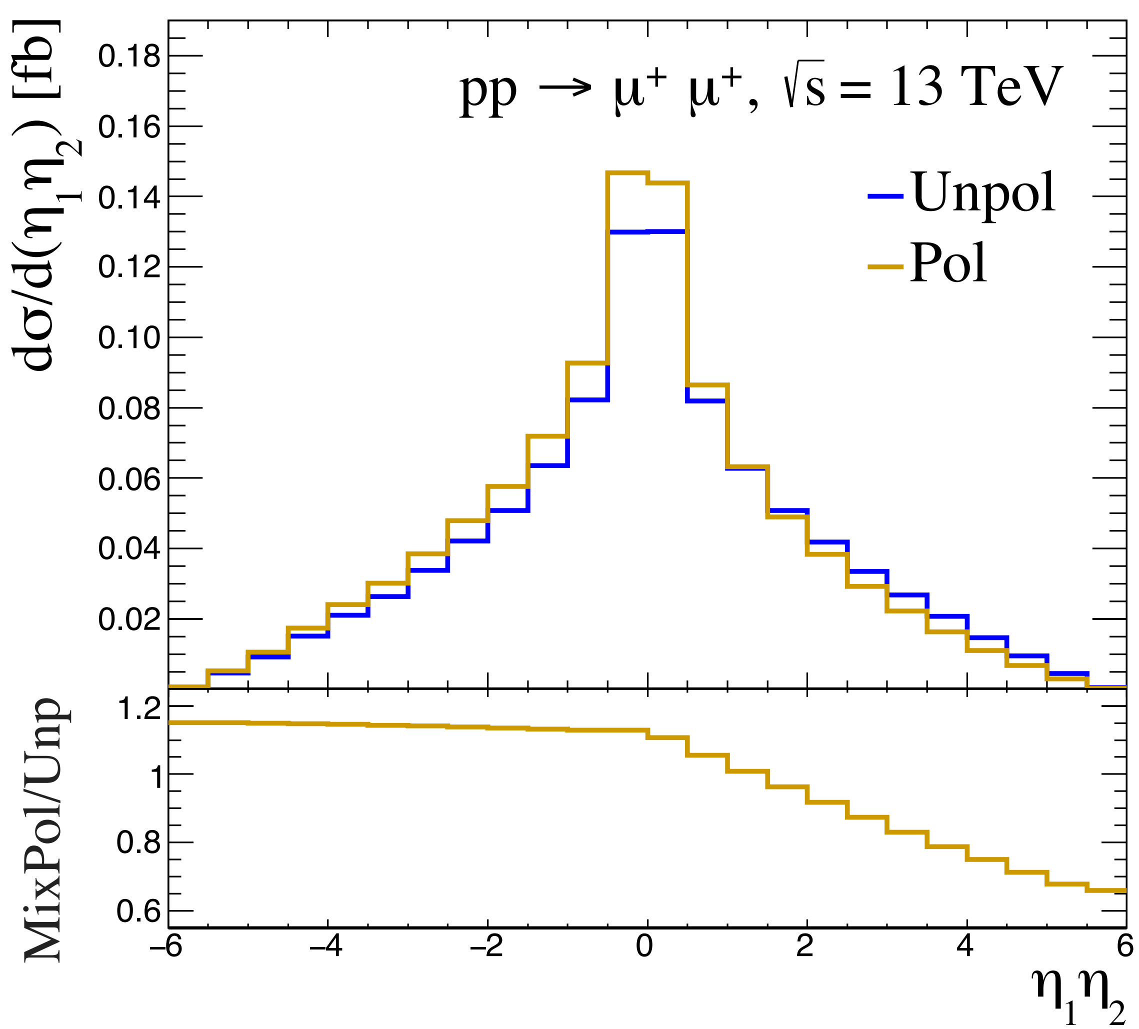
TAKING CARE OF THE BACKGROUND PROCESSES:

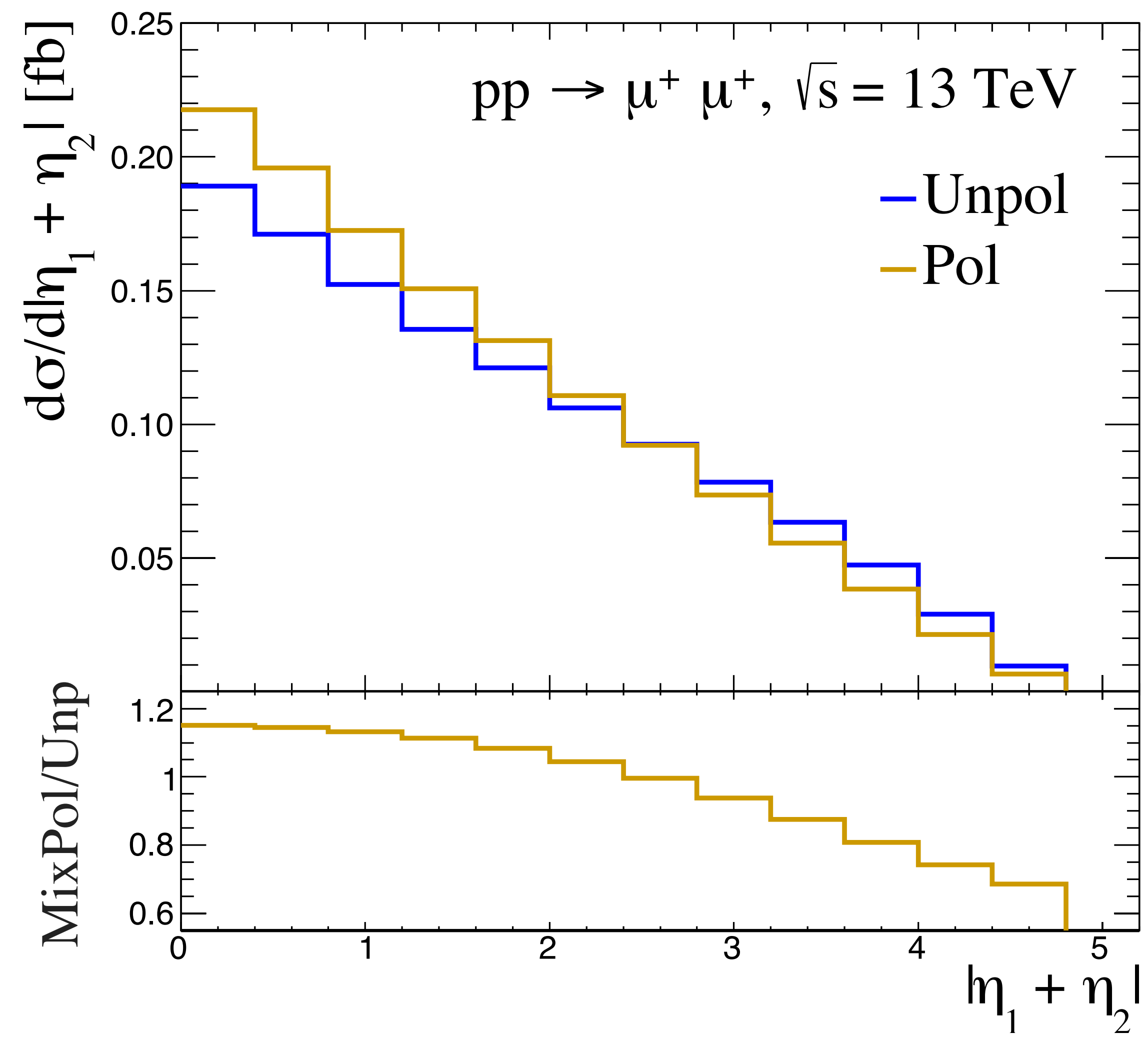
- $WW\,jj$: SPS equivalent to the DPS, the process is accompanied by two extra jets.
- WZ/ZZ production in which one muon from the Z decay is not detected.
- $t\bar{t}$ production: can produce a pair of positively charged muons.

FINAL SELECTION

PHASE-SPACE CUTS + THEORETICAL SUBTRACTION

$$|\eta_i| < 2.4, \quad 25\text{GeV} < k_T^{\text{lead}} < 50\text{GeV}, \quad 15\text{GeV} < k_T^{\text{subl}} < 40\text{GeV}, \quad k_T^{\mu_3} < 5\text{GeV},$$
$$\not{E}_T > 20\text{GeV}, \quad dR(\mu_1, \mu_2) > 0.1\,, \quad k_T^{\text{jet1}} < 50\text{GeV}\,, \quad k_T^{\text{jet2}} < 25\text{GeV}$$

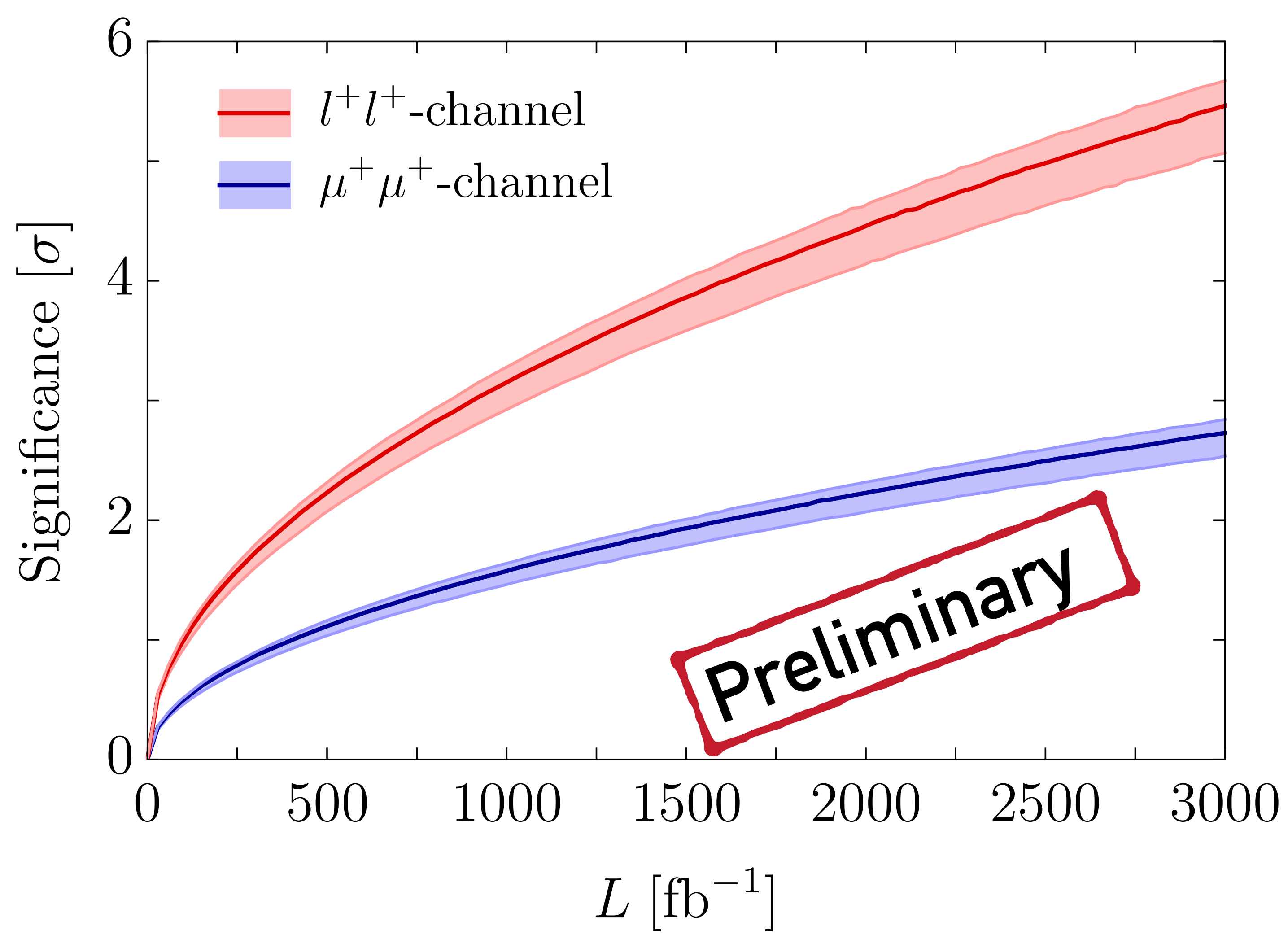




MEASURABLE AT THE LHC?

- Assuming that the background suppression is as effective as we predict, LHC can be sensitive to such values of the asymmetry in the near future

$\|\eta_i\|$	> 0	> 0.6	> 1.2
σ [fb]	0.51	0.29	0.13
$A\|_{\text{Mix-Pol}}$	0.07	0.11	0.16



PART IV

CONCLUSIONS

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- In double parton scattering the the final states produced in the two hard interactions are not independent of each other because parton correlations play a role.
- In particular, quark spin correlations play a role in creating distortions and asymmetries in the final state distributions.
- W boson pair production at the LHC is a very promising process for the study of polarized double parton distributions.
- We identify a promising observable to detect and measure such quark spin correlations.
- Within some assumption on the possibility of subtracting the background we predict that the measurement can be performed at the LHC in the near future.

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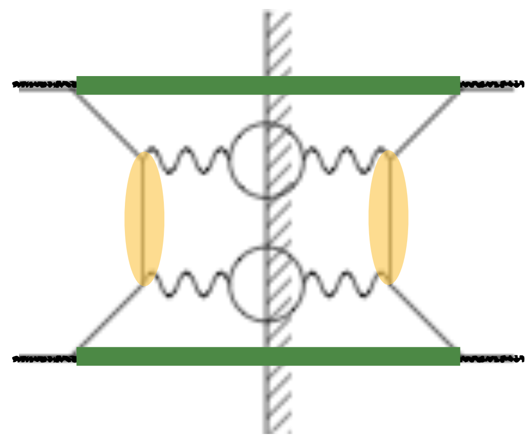
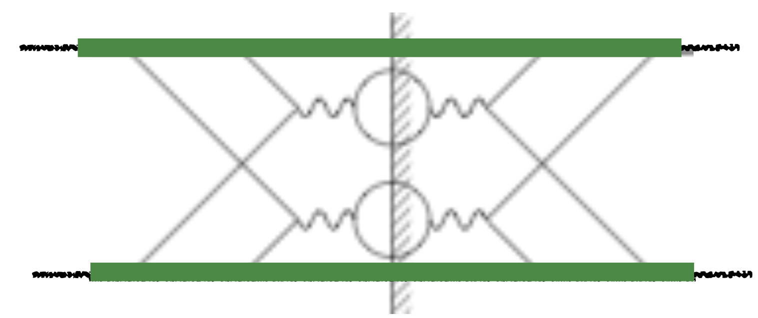
THANK YOU!

BACK-UP

SIMPLE POWER COUNTING FOR SINGLE AND DOUBLE DRELL-YAN

Double Drell-Yan → In each of the two hard interactions an electroweak gauge boson $(\gamma^*, Z, W^{\pm})$ is produced.
The process is driven by: $q\bar{q}$ annihilation - boson production - leptonic decay.

	SPS	DPS	
$Q^2 = x\bar{x}s$			
$\dfrac{s d\sigma}{\prod_{i=1,2} dx_i d\bar{x}_i}$	1	$\dfrac{\Lambda^2}{Q^2}$	$\dfrac{\sigma_{\text{DPS}}}{\sigma_{\text{SPS}}} \sim \dfrac{\Lambda^2}{Q^2}$
$\dfrac{s d\sigma}{\prod_{i=1,2} dx_i d\bar{x}_i d^2\boldsymbol{q}_{\perp i}}$	$\dfrac{1}{\Lambda^2 Q^2}$	$\dfrac{1}{\Lambda^2 Q^2}$	$\dfrac{\sigma_{\text{DPS}}}{\sigma_{\text{SPS}}} \sim 1$

[Diehl, Ostermeier, Schäfer, 2011]

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	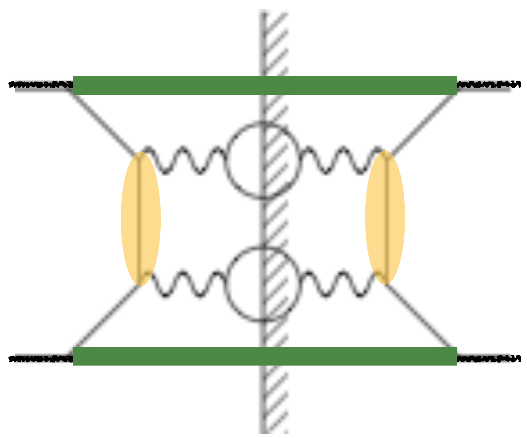	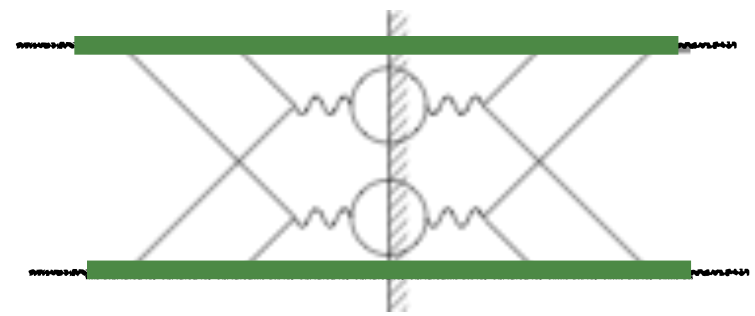	
$Q^2 = x\bar{x}s$			
$\dfrac{s\,d\sigma}{\prod_{i=1,2} dx_i d\bar{x}_i}$	1	$\dfrac{\Lambda^2}{Q^2}$	$\dfrac{\sigma_{\mathrm{DPS}}}{\sigma_{\mathrm{SPS}}} \sim \dfrac{\Lambda^2}{Q^2}$
$\dfrac{s\,d\sigma}{\prod_{i=1,2} dx_i d\bar{x}_i d^2\boldsymbol{q}_{\perp i}}$	$\dfrac{1}{\Lambda^2 Q^2}$	$\dfrac{1}{\Lambda^2 Q^2}$	$\dfrac{\sigma_{\mathrm{DPS}}}{\sigma_{\mathrm{SPS}}} \sim 1$

[Diehl, Ostermeier, Schäfer, 2011]

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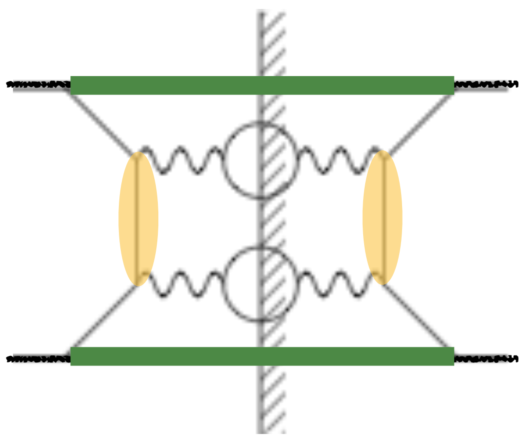
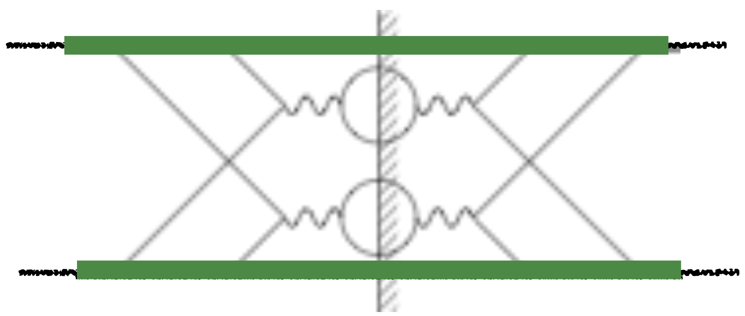
	SPS	DPS	
$Q^2 = x\bar{x}s$			
$\frac{s d\sigma}{\prod_{i=1,2} dx_i d\bar{x}_i}$	1	$\frac{\Lambda^2}{Q^2}$	$\frac{\sigma_{\mathrm{DPS}}}{\sigma_{\mathrm{SPS}}} \sim \frac{\Lambda^2}{Q^2}$
$\frac{s d\sigma}{\prod_{i=1,2} dx_i d\bar{x}_i d^2\boldsymbol{q}_{\perp i}}$	$\frac{1}{\Lambda^2 Q^2}$	$\frac{1}{\Lambda^2 Q^2}$	$\frac{\sigma_{\mathrm{DPS}}}{\sigma_{\mathrm{SPS}}} \sim 1$

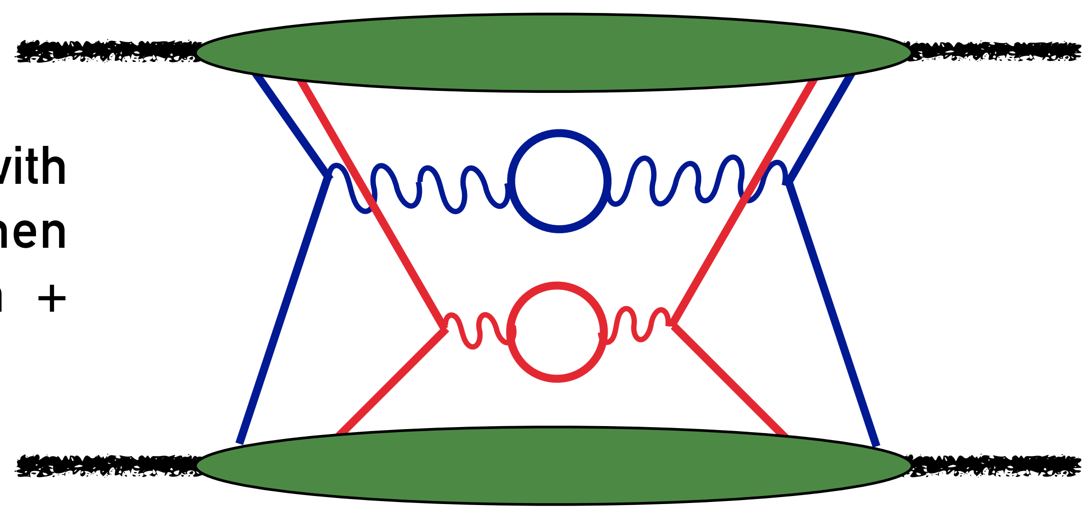
When not integrated over the boson transverse momenta, the single and the double contributions are comparable.

[Diehl, Ostermeier, Schäfer, 2011]

HOW TO ACCESS A TWO PARTON INFORMATION? DOUBLE PARTON SCATTERING!

Kulesza, Stirling,(2000)
Gaunt, Kom, Kulesza, Stirling,(2010)
Diehl, Kasemets(2012)

Production of two W bosons with the same charge which then decay leptonically (e.g. muon + neutrino).



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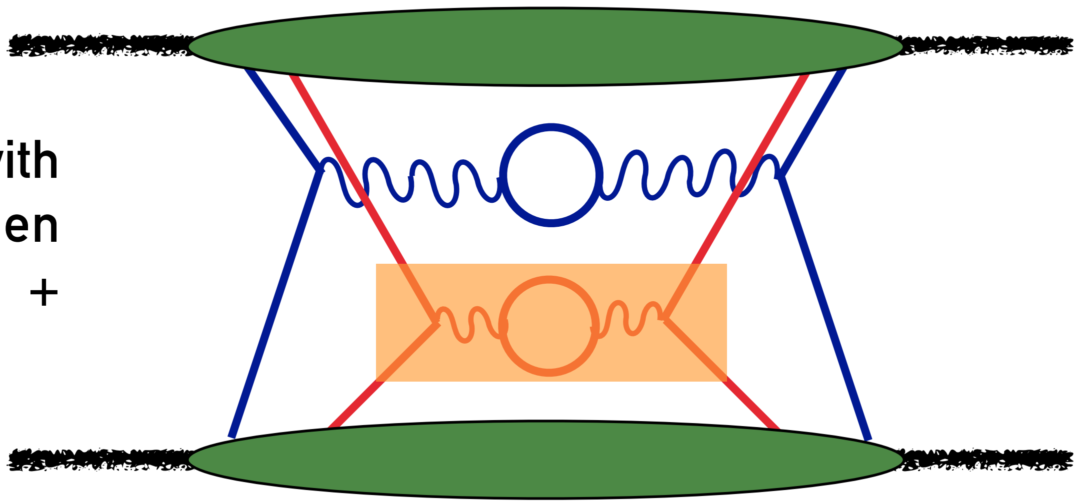

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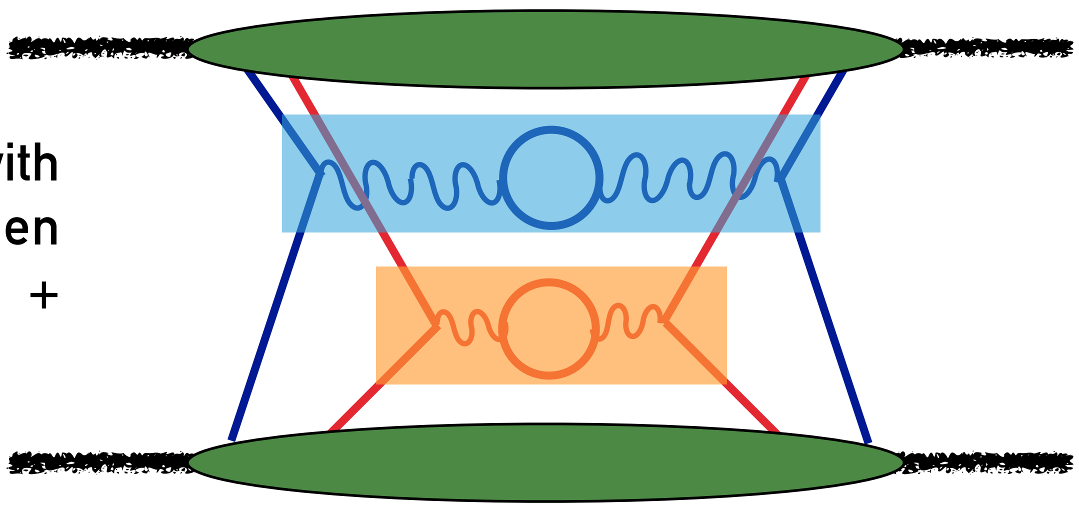

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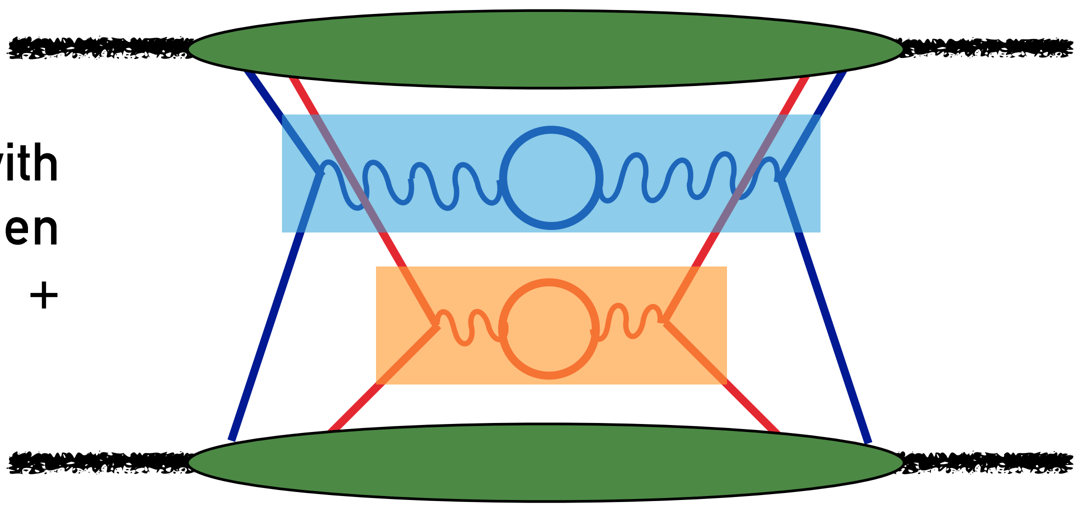
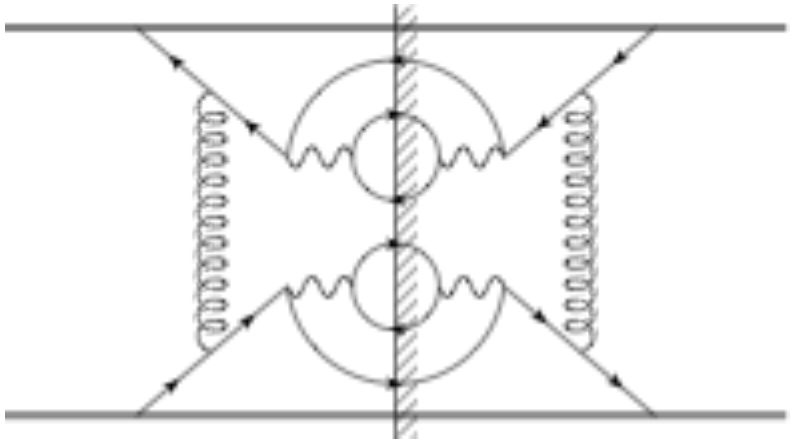


Paver, Treleani (1982); Mekhfi (1985)
Diehl, Ostermeier, Schäfer, (2011)

In the cross section of double W production the single scattering contribution is suppressed at the first order in the SM. This makes double parton scattering remarkably important in this case, The process is one of the most promising for studying the double Parton interactions and parton distributions.

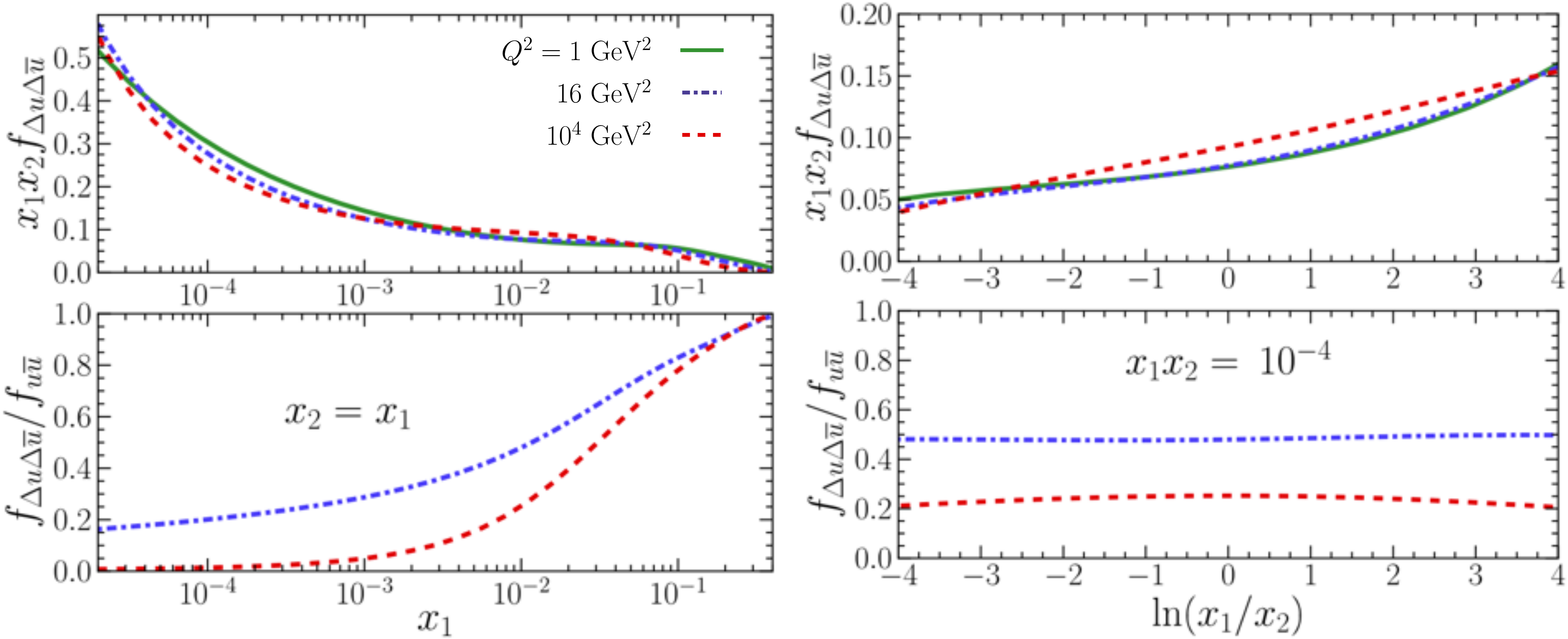


Manohar, Waalewijn (2012)

IMPACT OF LONGITUNAL POLARIZATION

Diehl, Kasemets(2012)

$$f_{p_1 p_2}(x_1, x_2, \boldsymbol{y}; Q) = \tilde{f}_{p_1 p_2}(x_1, x_2; Q)\, G(\boldsymbol{y})\,, \qquad G(\boldsymbol{y}) = 1$$



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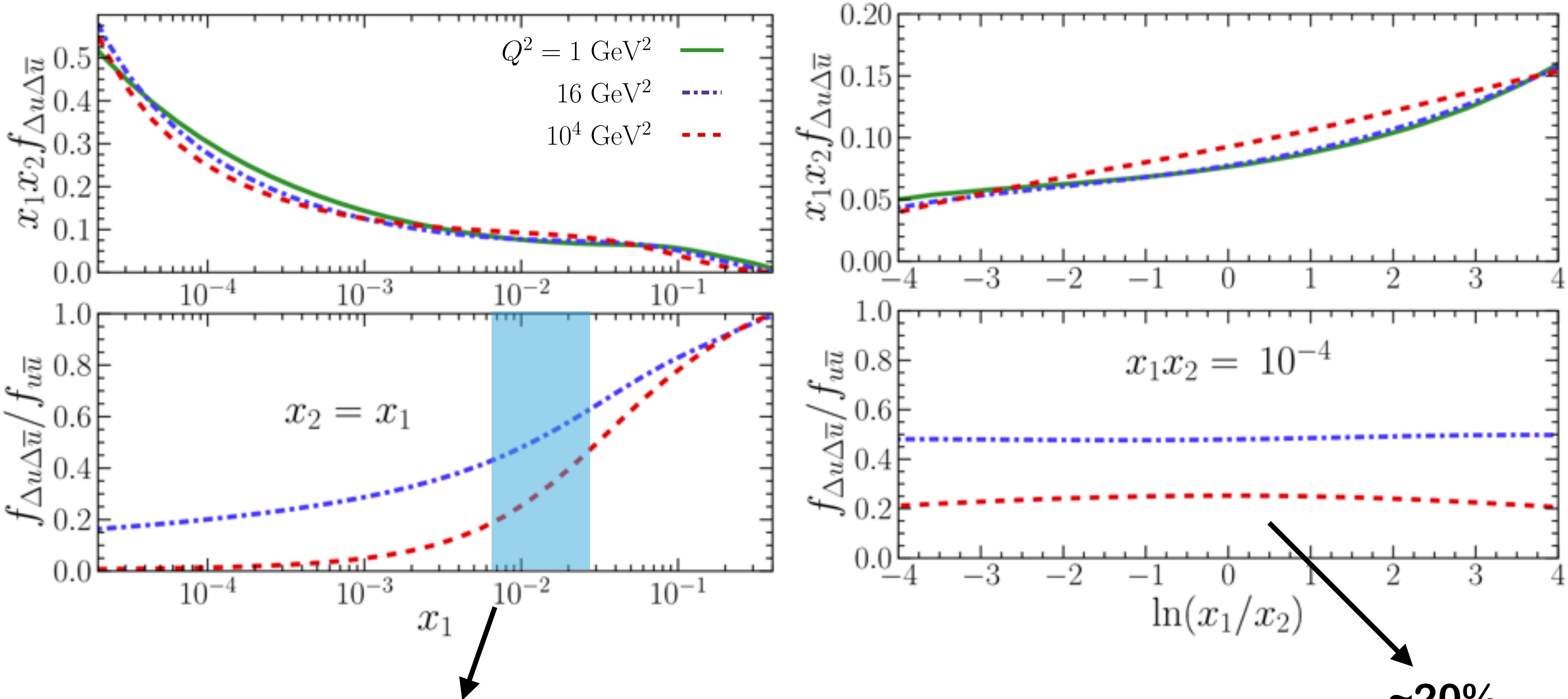

~20%

At values of Q and x typical of double W production the contribution of the longitudinal part can be relevant! Worth to be investigated deeper…