Production of like-sign W pairs via double parton scattering

Oskar Grocholski
in collaboration with Markus Diehl

Seminar "Theory of Particle Physics and Cosmology"

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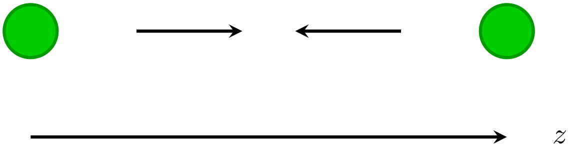
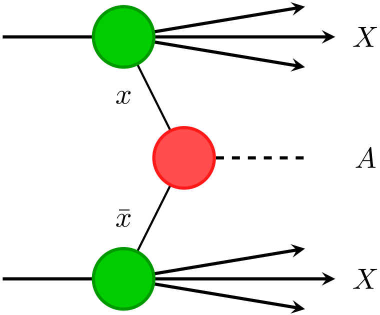
Single parton scattering



$$v^{\pm} = \frac{1}{\sqrt{2}}(v^0 \pm v^3)$$

Drell-Yan process: $pp' \longrightarrow A + X$



cross section $=$ parton distribution functions $\times$ parton-level cross section

Parton Distribution Function (PDF)

Definition of PDFs:

$$F_q(x;\mu) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p|\, \bar{q}\big(-z/2\big)\, \Gamma\, q\big(z/2\big)\, |p\rangle\, \Big|_{z^+=|\mathbf{z}|=0} . \qquad (1)$$

$\Gamma = \gamma^+,\ \gamma^5\gamma^+.$

Double parton scattering

$$pp' \to A_1 + A_2 + X$$

A_i – produced in hard processes, X – summed over.
Hard scales: $Q_1, Q_2 \gg \Lambda$.

See: M. Buffing, M. Diehl, T. Kasemets 2021 [arXiv:1708.03528]

This work:

$$pp' \longrightarrow W^{\pm}W^{\pm} + X$$

Like-sign W pair production: SPS vs DPS

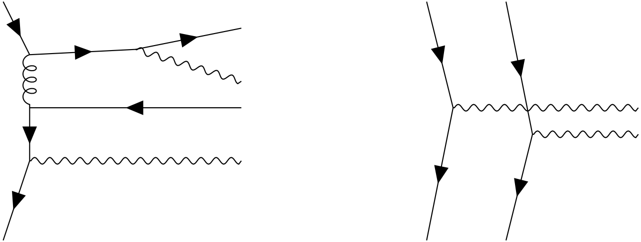


Figure: Single- (left) and double parton (right) Drell-Yan production of $W^{\pm}W^{\pm}$ pairs.

Like-sign W pair production: SPS vs DPS

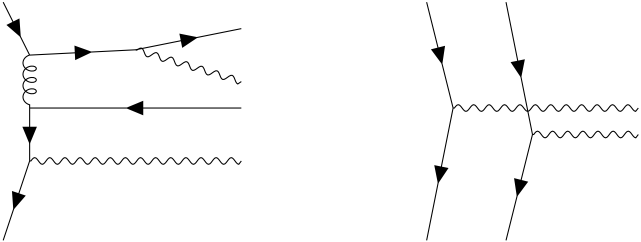


Figure: Single- (left) and double parton (right) Drell-Yan production of $W^{\pm}W^{\pm}$ pairs.

- $\sigma_{SPS} \propto \mathcal{O}(\alpha_S^2)$ with ≥ 2 jets.
- $\sigma_{DPS} \propto \mathcal{O}(\alpha_S^0)$,
- First observation of double parton scattering – CMS, Phys.Rev.Lett. 131 (2023).

Double parton factorization - an initial picture

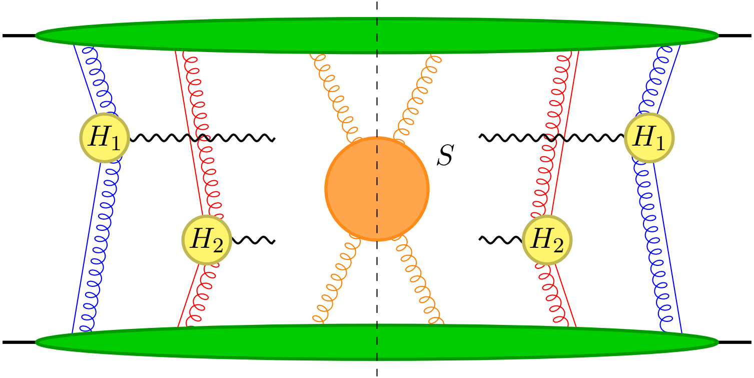
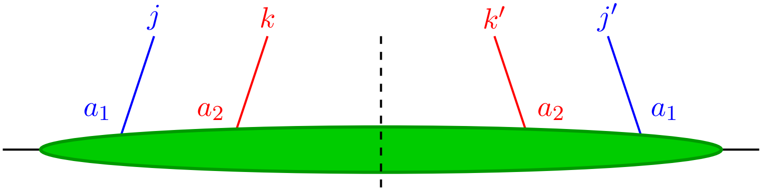


Figure: The general form of a leading-power graph representing the DPS.

Colour structure of DPDs



Parton carry colour indices $\rightarrow$ project on SU(3) representations.

For quarks one can either project on $\delta_{jj'}\delta_{kk'}$ (colour singlet) or $t^c_{jj'}t^c_{kk'}$ (colour octet).

Gluons: $1, 8_S, 8_A, 10, \overline{10}, 27$.

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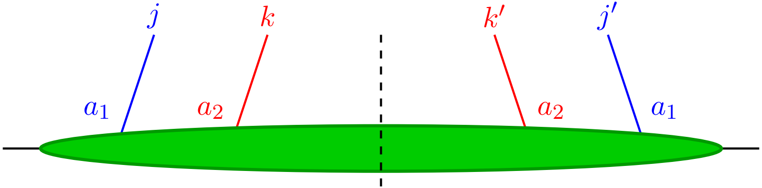

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Notation

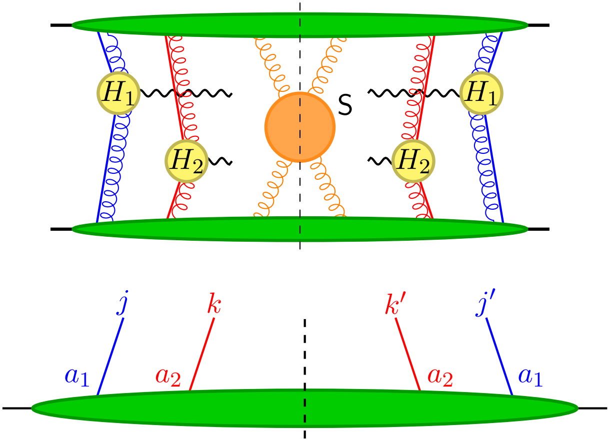
$^{R_1R_2}F_{a_1a_2}$ for parton a_i in representation R_i. $\dim(R_1) = \dim(R_2)$.

Evolution of DPDs

Roughly:

μ_1, μ_2 $\leftrightarrow$ cut-off on virtuality of parton 1 and 2.
$\rightarrow$ Double DGLAP evolution.

ζ $\leftrightarrow$ cut-off on soft gluons rapidities.
$\rightarrow$ Collins-Soper equation.



Double Drell-Yan production of $W^{\pm}W^{\pm}$

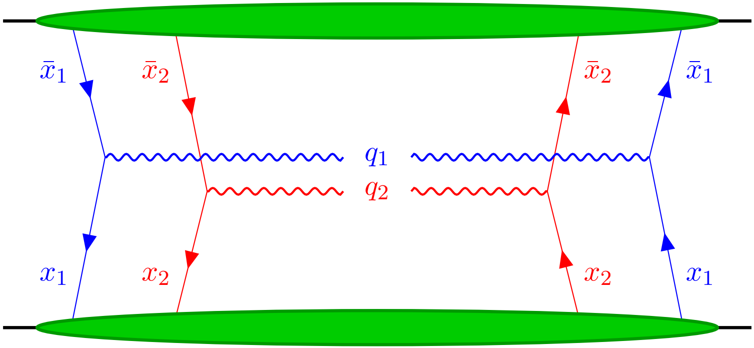
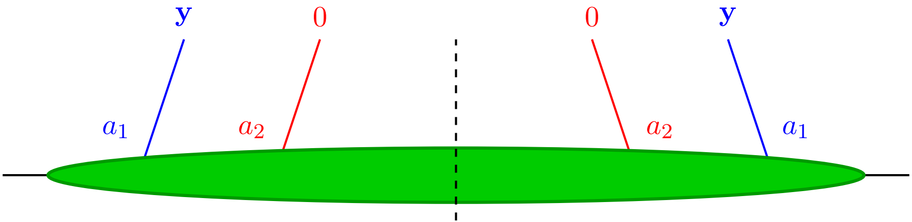


Figure: LO Feynman diagram representing the DPD contribution to $W^{\pm}W^{\pm}$ production.

Cross-section integrated over transverse momenta

$$\frac{d\sigma_{DPS}}{\prod_{i=1,2} dx_i d\bar{x}_i} = \frac{1}{1+\delta_{A_1 A_2}} \sum_{a,b} \hat{\sigma}_{a_1 b_1 \to A_1} \hat{\sigma}_{a_2 b_2 \to A_2} \times \int d^2\mathbf{y} \sum_{R_i} {}^{R_1 R_2} F^{coll.}_{a_1 a_2}(x_i, \mathbf{y}) \, {}^{\bar{R}_1 \bar{R}_2} F^{coll.}_{b_1 b_2}(\bar{x}_i, \mathbf{y}) \,. \tag{2}$$

Collinear DPDs



$\mathbf{y}$ – transverse distance between partons 1 and 2.

DTMD in the transverse position space

$$\frac{d\sigma_{DPS}}{\prod_{i=1,2} dx_i d\bar{x}_i d^2\mathbf{q}_i} = \frac{1}{1+\delta_{A_1A_2}} \sum_{a,b} \hat{\sigma}_{a_1b_1\to A_1} \hat{\sigma}_{a_2b_2\to A_2}$$
$$\times \prod_{i=1,2} \int d^2\mathbf{k}_i \, d^2\bar{\mathbf{k}}_i \, \delta^{(2)}\left(\mathbf{q}_i - \mathbf{k}_i - \bar{\mathbf{k}}_i\right)$$
$$\times \int d^2\mathbf{y} \sum_{R_i} {}^{R_1R_2}F_{a_1a_2}\left(x_i, \mathbf{k}_i, \mathbf{y}\right) {}^{\bar{R}_1\bar{R}_2}F_{b_1b_2}\left(\bar{x}_i, \bar{\mathbf{k}}_i, \mathbf{y}\right) . \qquad (3)$$

DTMD in the transverse position space

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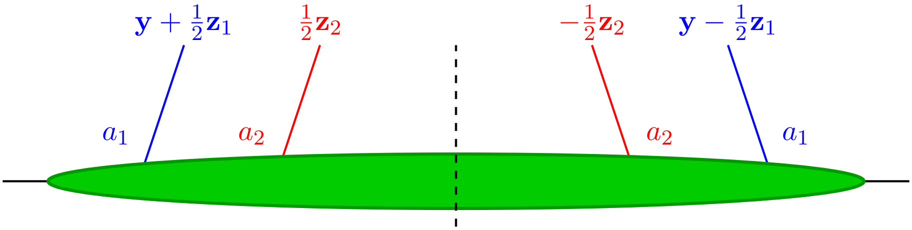

$\mathbf{y}_\pm = \mathbf{y} \pm \frac{1}{2}(\mathbf{z}_1 - \mathbf{z}_2)$ – distance between parton pairs on the left/right.

Large transverse momenta

$$\frac{d\sigma^{DPS}}{\prod_{i=1,2} dx_i d\bar{x}_i d^2\mathbf{q}_i}$$

$$\propto \sum_{a_1,a_2,b_1,b_2} \hat{\sigma}_{a_1b_1}(Q_1^2;\mu_1)\hat{\sigma}_{a_2b_2}(Q_2^2;\mu_2)$$

$$\times \int \frac{d^2\mathbf{z}_1}{(2\pi)^2}\frac{d^2\mathbf{z}_2}{(2\pi)^2} d^2\mathbf{y}\; e^{-i\mathbf{q}_1\mathbf{z}_1 - i\mathbf{q}_2\mathbf{z}_2}$$

$$\times \sum_{R_i} {}^{R_1R_2}F_{a_1a_2}(x_i,\mathbf{z}_i,\mathbf{y})\,{}^{\bar{R}_1\bar{R}_2}F_{b_1b_2}(\bar{x}_i,\mathbf{z}_i,\mathbf{y})$$

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$$\times \sum_{R_i} {}^{R_1R_2}F_{a_1a_2}(x_i,\mathbf{z}_i,\mathbf{y})\, {}^{\bar{R}_1\bar{R}_2}F_{b_1b_2}(\bar{x}_i,\mathbf{z}_i,\mathbf{y})$$

$\Lambda \ll |\mathbf{q}_i| \ll Q_i$

Additional assumption about the scales:

$$\Lambda \ll |\mathbf{q}_i| \ll Q_i$$

$\implies$ the most important contribution from the region of small $\mathbf{z}_i$:

$$|\mathbf{z}_i| \lesssim |\mathbf{q}_i|^{-1} \ll \Lambda^{-1}.$$

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We need to consider 2 sub-regions:

- $|\mathbf{y}| \sim |\mathbf{z}| \ll \Lambda^{-1}$: DTMD can be expressed in terms of PDFs (splitting) and twist-four distributions.
- $|\mathbf{y}| \gg |\mathbf{z}|$: use operator product expansion to match DTMDs onto collinear double parton distributions (DPDF).

Large y approximation

Assume $|\mathbf{y}| \gg |\mathbf{z}_i|$.

Let us apply the operator product expansion to operators defining DTMDs:

$$ {}^{R}\mathcal{O}_a(x_i, \mathbf{y}, \mathbf{z}) = \sum_b \sum_{R'} {}^{R\bar{R}'}C_{ab}(x', \mathbf{z}) \underset{x}{\otimes} {}^{R'}\mathcal{O}_b(x', \mathbf{y}, \mathbf{z} = 0). \tag{5} $$

Matrix elements of a product of two $\mathcal{O}_b(x', \mathbf{y}, \mathbf{z} = 0)$ define collinear DPDFs.

Large y approximation

Matching formula

$$ {}^{R_1 R_2}F_{a_1,a_2}(x, \bar{x}, \mathbf{y}, \mathbf{z}_i; \mu_{0i}, \zeta) = \sum_{b_1,b_2} \sum_{R_1',R_2'} {}^{R_1 \bar{R}_1'}C_{a_1 b_1} \underset{x_1}{\otimes} {}^{R_2 \bar{R}_2'}C_{a_2 b_2} \underset{x_2}{\otimes} {}^{R_1' R_2'}F^{coll.}_{b_1 b_2}(x_i', \mathbf{y}; \mu_{0i}, \zeta) \,, \tag{6} $$

with the kernels

$$ {}^{R_1 \bar{R}_1'}C_{a_1 b_1} = {}^{R_1 \bar{R}_1'}C_{a_1 b_1}(x_1, \mathbf{z}_1; \mu_{01}, x_1^2 \zeta), \tag{7} $$

known up to order α_S in both colour channels.

For reference see: M. Buffing, M. Diehl, T. Kasemets 2021 [arXiv:1708.03528]

Scales in the problem

- The natural choice of scales, at which DPDFs is computed, is given by $|\mathbf{y}^*|$:

$$\mathbf{y}^* = \begin{cases} \sim \mathbf{y} & \text{for } |\mathbf{y}| \ll y_{max} \\ \sim y_{max} & \text{for } |\mathbf{y}| \gtrsim y_{max} \end{cases} \tag{8}$$

- Matching should be computed at scales $\mu_{0i} \propto 1/|\mathbf{z}_i|$
  $\rightarrow$ evolve DPDFs to the matching scales using DGLAP equation.

Scales in the problem

- Rapidity dependence $\to$ use the Collins-Soper equation for the matching kernels:

$$\frac{\partial}{\partial \log \sqrt{\zeta}} {}^{R_1 R_1'}C_{a_1 b_1}\left(x_1, \mathbf{z}_1; \mu_1, \zeta\right) = {}^{R_1}K_{a_1}(\mathbf{z}_1; \mu_1)^{R_1 R_1'}C_{a_1 b_1}\left(x_1, \mathbf{z}_1; \mu_1, \zeta\right) . \quad (9)$$

${}^{R_1}K_{a_1}$ = colour factor $\times$ singlet TMD Collins-Soper kernel.

Solution

$${}^{R_1 R_1'}C_{a_1 b_1}\left(x_1, \mathbf{z}_1; \mu_1, \zeta'\right) = \exp\left({}^{R_1}K_{a_1}(\mathbf{z}_1; \mu_1) \log \frac{\sqrt{\zeta'}}{\sqrt{\zeta}}\right){}^{R_1 R_1'}C_{a_1 b_1}\left(x_1, \mathbf{z}_1; \mu_1, \zeta\right) . \quad (10)$$

Scales in the problem

Finally, matched DTMDs are evolved to the final scales $\sim Q_i$

Evolution equations for DTMDs

$$\frac{\partial}{\partial \log \sqrt{\zeta}} {}^{R_1 R_2}F_{a_1 a_2} = \left[{}^{R_1}J(\mathbf{y};\mu_i) + {}^{R_1}K(\mathbf{z}_1;\mu_1) + {}^{R_2}K(\mathbf{z}_2;\mu_2)\right] {}^{R_1 R_2}F_{a_1 a_2} \,,$$
$$\frac{\partial}{\partial \log \mu_1} {}^{R_1 R_2}F_{a_1 a_2} = \left[\gamma_{a_1} - \gamma_{K,a_1} \log \frac{x_1\sqrt{\zeta}}{\mu}\right] {}^{R_1 R_2}F_{a_1 a_2} \,. \tag{11}$$

${}^{1}J = 0$ **at all orders!**

Effects of the rapidity evolution

Solution of the Collins-Soper equation for DTMDs

$$
{}^{R_1R_2}F_{a_1a_2}(x_i, \mathbf{z}_i, \mathbf{y}; \mu_{0i}, \zeta)
$$
$$
= \exp\left(\left[{}^{R_1}J(\mathbf{y};\mu_{0i}) + {}^{R_1}K(\mathbf{z}_1;\mu_{01}) + {}^{R_2}K(\mathbf{z}_2;\mu_{02})\right] \log\frac{\sqrt{\zeta}}{\sqrt{\zeta_0}}\right) {}^{R_1R_2}F_{a_1a_2}(x_i, \mathbf{z}_i, \mathbf{y}; \mu_{0i}, \zeta_0). \tag{12}
$$

Large-y behavior of the Collins-Soper kernel J – see [arXiv:2310.16432]

$$
{}^{R}J(\mathbf{y};\mu_i) = {}^{R}J^{pert.}(\mathbf{y}^*;\mu_i) + \Delta\, {}^{R}J(\mathbf{y}) \,, \quad \mathbf{y}^* - \text{regularized distance}, \tag{13}
$$

$\Delta\, {}^{8}J$ is $\mathcal{O}(-1)$ at large $\mathbf{y}$.

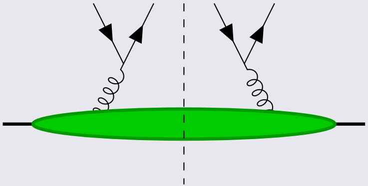
For large final scales one has a strong suppression of the color non-singlet channel at large $\mathbf{y}$.

Cross section in the large-y approximation

$$\frac{d\sigma_{DPS}}{\prod_{j=1,2} dx_i d\bar{x}_i d^2\mathbf{q}_i} = \frac{1}{1+\delta_{A_1A_2}} \sum_{a,b} \hat{\sigma}_{a_1b_1}\hat{\sigma}_{a_2b_2} \prod_{i=1,2} \int dz_i \, \frac{z_i}{2\pi} J_0(|\mathbf{q}_i|z_i)$$
$$\times \int_{y_{\text{cutoff}}}^{\infty} dy \, (2\pi y) \sum_{R} {}^{R_1R_2}F_{a_1a_2} {}^{\bar{R}_1\bar{R}_2}F_{b_1b_2} \, . \qquad (14)$$

Initial conditions for collinear DPDs

Splitting part



Perturbative splitting at scale $\propto |\mathbf{y}^*|^{-1}$
$\times$ Gaussian to suppress at large $\mathbf{y}$.

Intrinsic part

Product of PDFs $\times$ further factors, see Diehl, Gaunt, Lang, Plößl, Schäfer [2001.10428].

$$ {}^{R_1 R_2}F_{ab}^{intr.} = \text{colour factor}(R_1 R_2) \times {}^{11}F_{ab}^{intr.} \,. \tag{15} $$

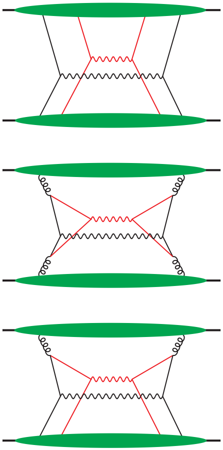
This form saturates the positivity bounds in colour space.

Combining the intrinsic and splitting parts

$$2v2 \leftrightarrow F^{intr.} F^{intr.}$$

$$1v1 \leftrightarrow F^{spl.} F^{spl.}$$

$$1v2 \leftrightarrow F^{spl.} F^{intr.}$$



Numerical results – matched DTMDs in z-space

- ChiliPDF – C++ library for evolution and interpolation of parton distributions
  Diehl, Nagar, Plößl, Tackmann [2305.0484]

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Numerical results – matched DTMDs in $\mathbf{z}$-space

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- Large distance Collins-Soper kernels as in Scimeni, Vladimirov [1912.06532]
- Hard scales $\mu_i = \sqrt{\zeta} = M_W$, $\sqrt{s} = 13$ TeV.
- $x_1 = x_2 = M_W/(13\ \mathrm{TeV}) \approx 6 \times 10^{-3}$.
- $|\mathbf{z}_1| = 0.1\ \mathrm{GeV}^{-1} =$ const.

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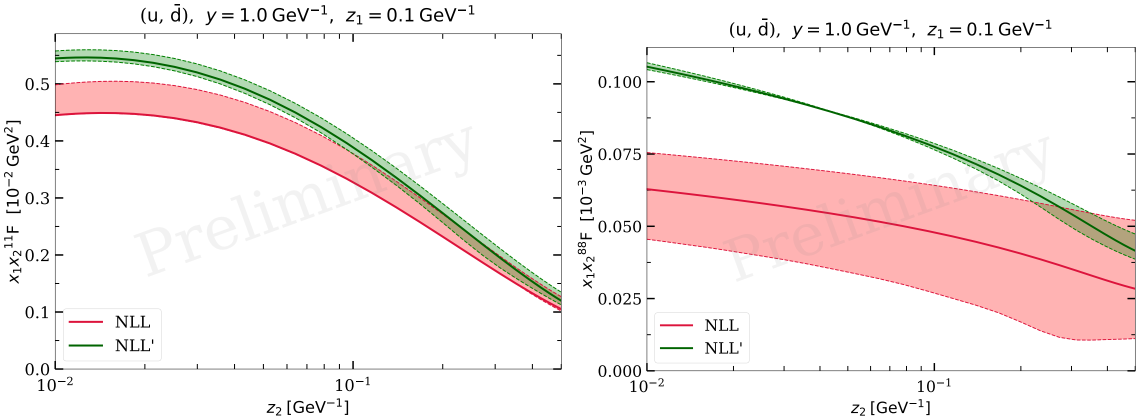
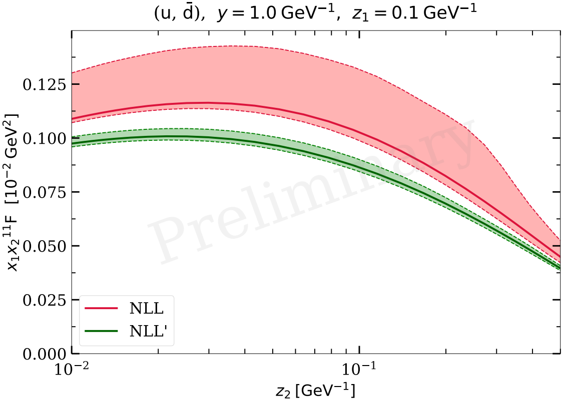
- $x_1 = x_2 = M_W/(13\,\mathrm{TeV}) \approx 6 \times 10^{-3}$.
- $|\mathbf{z}_1| = 0.1\,\mathrm{GeV}^{-1}$ = const.
- Estimation of higher-order corrections
  → vary the matching scale from $\frac{1}{2}\frac{b_0}{|\mathbf{z}^*|}$ to $\frac{2b_0}{|\mathbf{z}^*|}$.

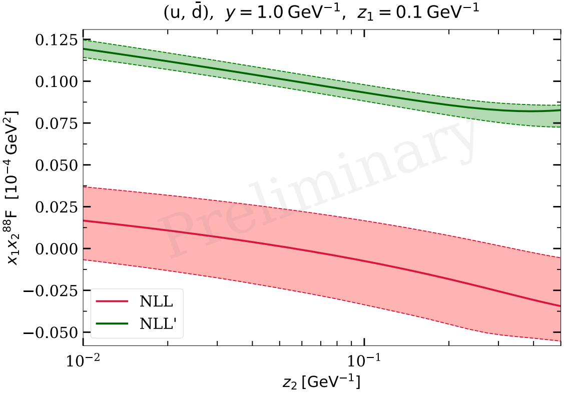
Numerical results – matched intrinsic DTMDs in z-space



Unpolarized DTMDs matched onto intrinsic DPDFs. Left: singlet, right: colour octet.
Bands represent the uncertainty estimation obtained by varying the matching scales.

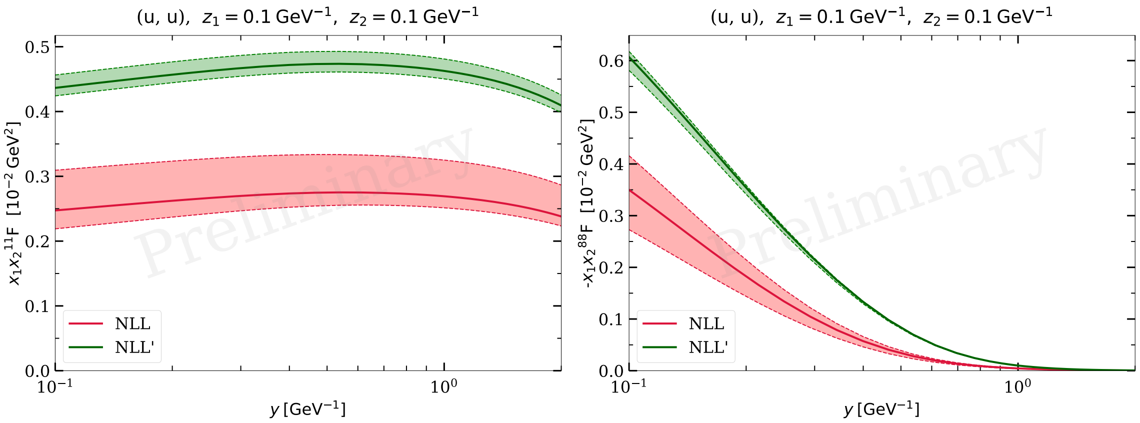
Numerical results – matched intrinsic DTMDs in z-space





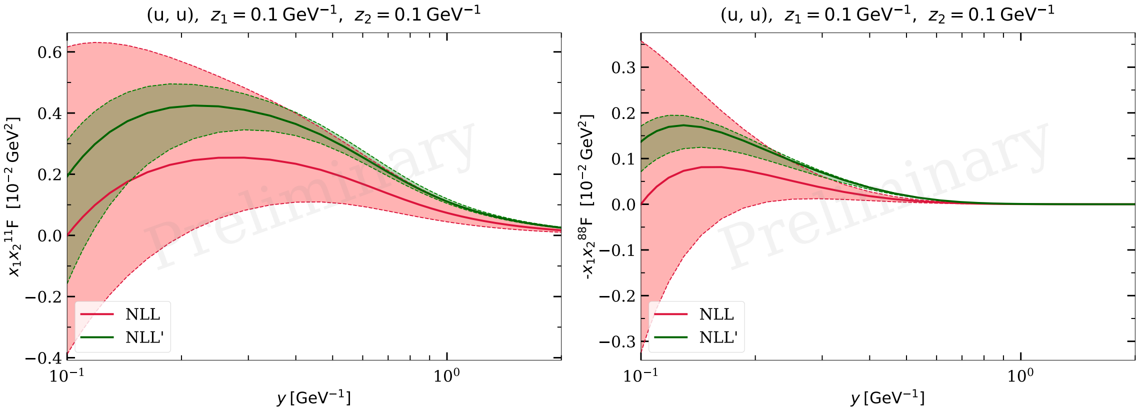
The same, but for longitudinally polarized quarks. Left: singlet, right: colour octet. Bands represent the uncertainty estimation obtained by varying the matching scales.

Numerical results – matched intrinsic DTMDs in y-space



Unpolarized DTMDs matched onto intrinsic DPDFs. Left: singlet, right: colour octet.
Bands represent the uncertainty estimation obtained by varying the matching scales.

Numerical results – matched splitting DTMDs in y-space

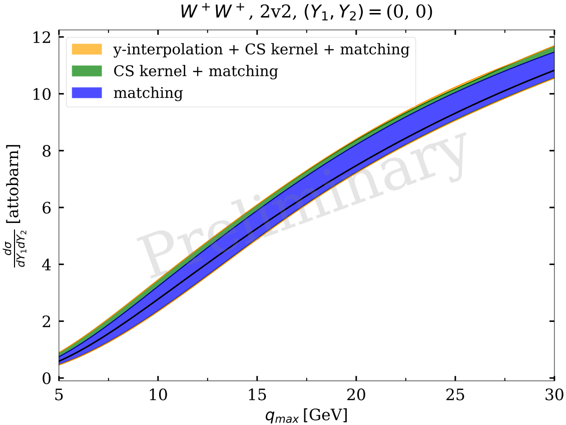


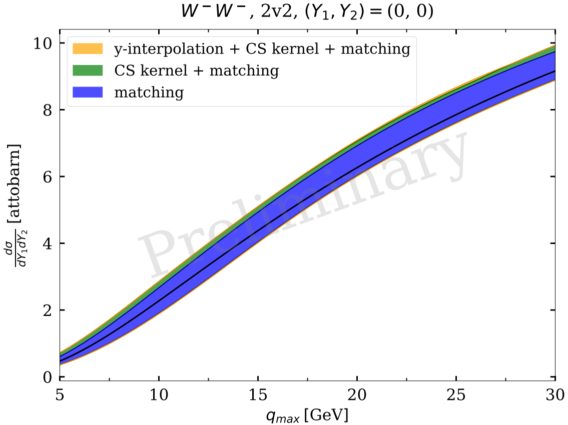
Unpolarized DTMDs matched onto intrinsic DPDFs. Left: singlet, right: colour octet.
Bands represent the uncertainty estimation obtained by varying the matching scales.

Numerical results – cross section of $W^{\pm}W^{\pm}$ production

- Singlet contributions much larger than nonsinglet:
  - like-sign W: $\sigma^{\text{singlet}} \sim 10^3 \times \sigma^{\text{nonsinglet}}$.
  - opposite-sign W: $\sigma^{\text{singlet}} \sim 10^2 \times \sigma^{\text{nonsinglet}}$.
- For like-sign W pair cross section dominated by the intrinsic part: $\sigma^{intr.} \sim 10 \times \sigma^{1v2} \sim 20 \times \sigma^{split.}$
- Opposite-sign W: splitting and intrinsic terms give similar contributions.

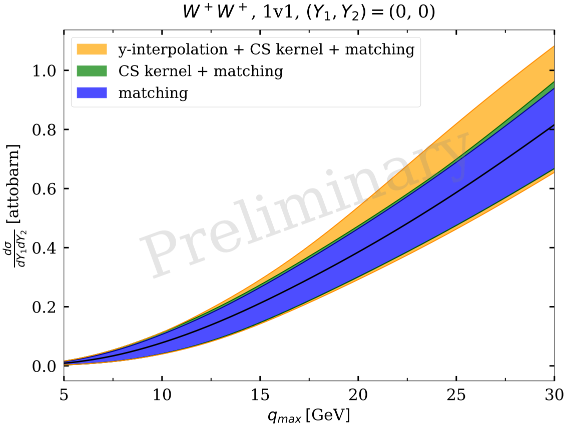
Partially integrated cross-sections – 2v2

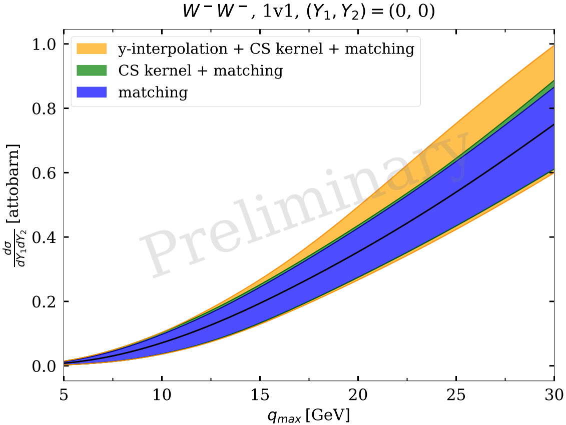




$\frac{d\sigma^{DPS,2v2}}{\prod_{i=1,2} d\mathbf{q}_i dY_i}$ integrated over the transverse momenta $|\mathbf{q}| < q_{max}$.

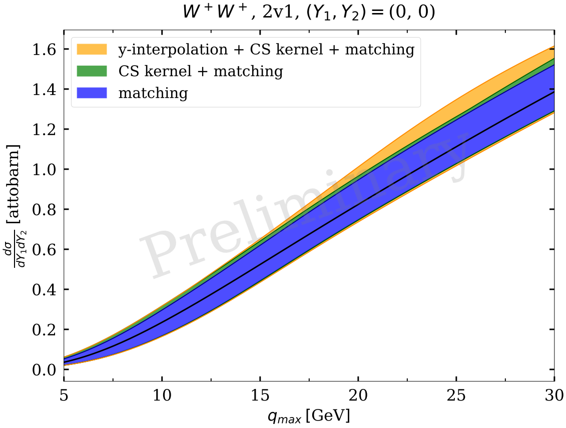
Partially integrated cross-sections – 1v1

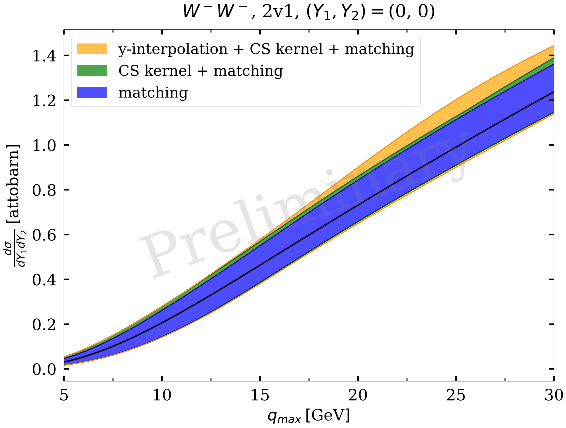




$\frac{d\sigma^{DPS,1v1}}{\prod_{i=1,2} d\mathbf{q}_i dY_i}$ integrated over the transverse momenta $|\mathbf{q}| < q_{max}$.

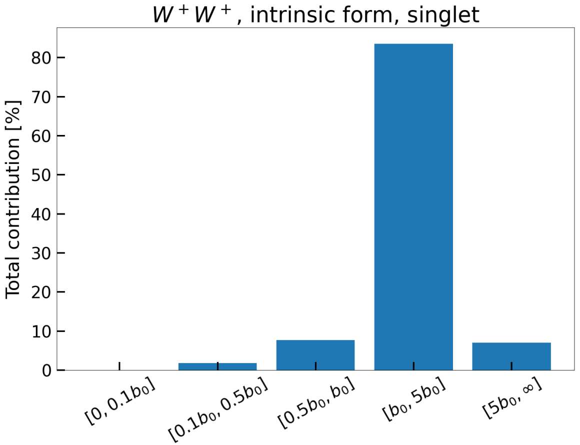
Partially integrated cross-sections – 2v1





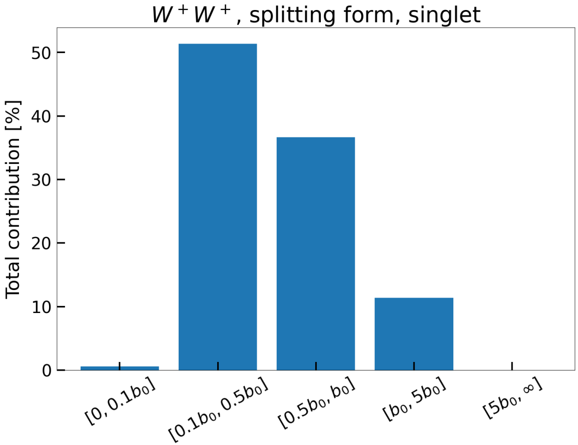
$\frac{d\sigma^{DPS,2v1}}{\prod_{i=1,2} d\mathbf{q}_i dY_i}$ integrated over the transverse momenta $|\mathbf{q}| < q_{max}$.

Contributions from different y-regions - intrinsic DPDFs.



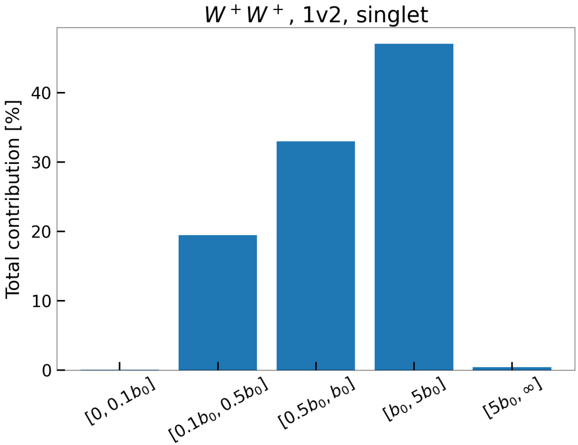
Contribution to differential cross section at zero rapidity integrated over $\mathbf{q}_T$ up to 20 GeV.

Contributions from different y-regions - splitting DPDFs.



Contribution to differential cross section at zero rapidity integrated over $\mathbf{q}_T$ up to 20 GeV.

Contributions from different y-regions - 1v2



Contribution to differential cross section at zero rapidity integrated over $\mathbf{q}_T$ up to 20 GeV.

Cross section in the short-distance approximation

DTMDs at initial scales expressed in terms of the splitting and intrinsic parts.

- Intrinsic part: $\mathbf{y} = 0$ limit of DPDF intrinsic part.

Cross section in the short-distance approximation

DTMDs at initial scales expressed in terms of the splitting and intrinsic parts.

- Intrinsic part: $\mathbf{y} = 0$ limit of DPDF intrinsic part.
- Splitting part (known only at LO)

$$ {}^{R_1 R_2}F^{spl.}_{a_1 a_2}(x_i, \mathbf{y}, \mathbf{z}_i; \mu_0) = \frac{\mathbf{y}^i_+ \mathbf{y}^j_-}{\mathbf{y}^2_+ \mathbf{y}^2_-} \frac{\alpha_s(\mu_0)}{2\pi^2} \, {}^{R_1 R_2}T^{ij}_{a_0 \to a_1 a_2}\left(\frac{x_1}{x_1 + x_2}\right) \frac{f_{a_0}(x_1 + x_2)}{x_1 + x_2} \,, \tag{16} $$

$$ \mathbf{y}_\pm = \mathbf{y} \pm \frac{1}{2}(\mathbf{z}_1 - \mathbf{z}_2) \,. \tag{17} $$

Note: no LO splitting contribution for like-sign W production.

Only one initial scale (contrary to the large-y case), chosen as

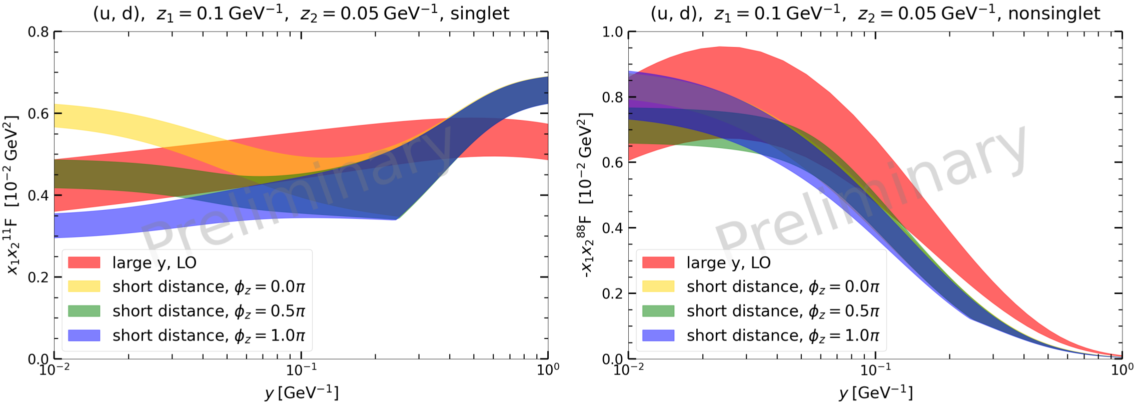
$$ \mu_0(\mathbf{y}, \mathbf{z}_1, \mathbf{z}_2) = b_0 / \sqrt{|\mathbf{y}^*_+| \times |\mathbf{y}^*_-|}. \tag{18} $$

Rapidity dependence

Collins-Soper equation for DTMDs at small distances mixes color representations:

$$\frac{\partial}{\partial \log \zeta} {}^{R_1 R_2}F_{a_1 a_2}(x_i, y; \mu, \zeta) = \frac{1}{2} {}^{R_1 R_2 R_1' R_2'}K_{a_1 a_2}(\mathbf{y}, \mathbf{z}_i; \mu) {}^{R_1' R_2'}F_{a_1 a_2}(x_i, y; \mu_i, \zeta) \,. \tag{19}$$

Numerical results – short-distance vs large-y DTMDs in y-space.



Intrinsic DTMDs in two approximations. Left: singlet, right: colour octet.
Presented are results for $\mathbf{y} \perp (\mathbf{z}_1 - \mathbf{z}_2)$ and different angles between $\mathbf{z}_1$ and $\mathbf{z}_2$.

Cross section in the short-distance region

$\int d^2\mathbf{y} \sum_R {}^{R_1R_2}F_{a_1a_2}{}^{\bar{R}_1\bar{R}_2}F_{b_1b_2}$ depends on angle between $\mathbf{z}_1$ and $\mathbf{z}_2$
$\implies$ cannot reduce the Fourier transform to integrals with J_0.

One can write

$$\int d^2\mathbf{y} \sum_R {}^{R_1R_2}F_{a_1a_2}{}^{\bar{R}_1\bar{R}_2}F_{b_1b_2} = \sum_{n=0}^{\infty} \cos(n\varphi_z) W_{a_1a_2b_1b_2,n}(|\mathbf{z}_i|), \tag{20}$$

where φ_z is angle between $\mathbf{z}_1$ and $\mathbf{z}_2$.

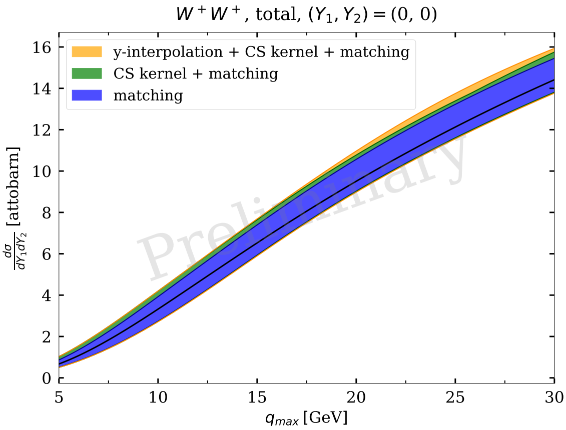
Cross section in the short-distance region

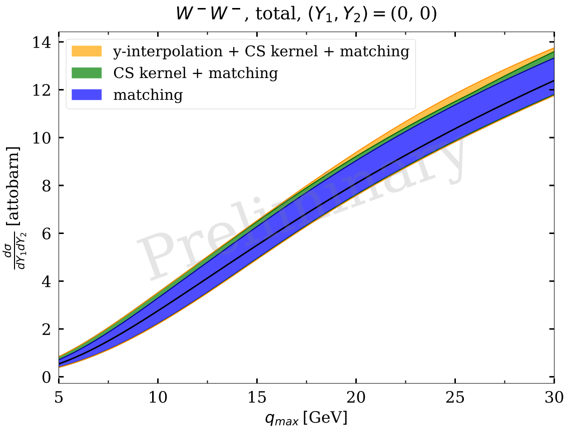
$$\frac{d\sigma_{DPS}}{\prod_{j=1,2} dx_i d\bar{x}_i d^2\mathbf{q}_i} = \frac{1}{1+\delta_{A_1A_2}} \sum_{a,b} \hat{\sigma}_{a_1b_1}\hat{\sigma}_{a_2b_2} \sum_{n=0}^{\infty} \cos(n\phi_q) \times \prod_{i=1,2} \int dz_i \, \frac{z_i}{2\pi} J_n(|\mathbf{q}_i|z_i) W_{a_1a_2b_1b_2,n}(|\mathbf{z}_i|) \, . \tag{21}$$

ϕ_q - angle between $\mathbf{q}_1$ and $\mathbf{q}_2$.

- Angular correlations between momenta of produced W bosons.
- Double Bessel integrals of different orders computed using Levin's method implemented in ChiliPDF.
  D. Levin Fast integration of rapidly oscillatory functions, J. of Computational and Applied Mathematics 67 (1996) 95-101

Final results for like-sign W pairs production



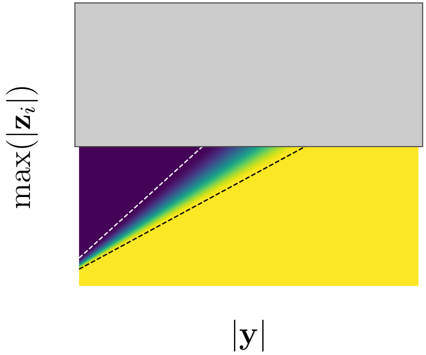


$\frac{d\sigma^{DPS}}{\prod_{i=1,2} d\mathbf{q}_i dY_i}$ integrated over the transverse momenta $|\mathbf{q}| < q_{max}$.

Summary

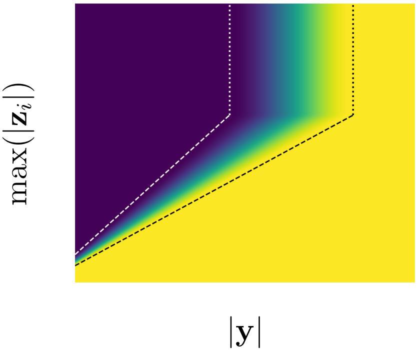
- Using the operator product expansion we obtain the description of DPS at large transverse momenta.
- Large-y approximation $\rightarrow$ dominant contribution from the singlet intrinsic part in the region of nonperturbative $\mathbf{y}$.
- Contribution from non-singlet DPDs to like-sign W production is strongly suppressed.
- Only the intrinsic part contributes to the short-distance part of like-sign W pair production cross section.
- Future work:
  - Computation of the short-distance contribution to W^+W^- production.
  - Study of uncertainties in the short-distance region.

Backup – interpolating between two regions



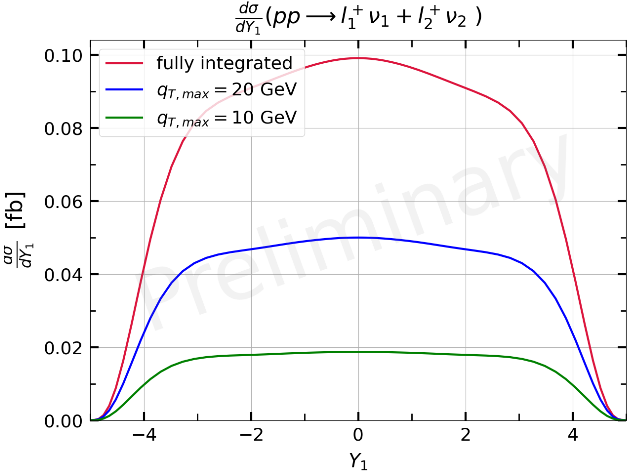
- Small $\mathbf{z} \to$ interpolate between two approximations in the overlap region.

Backup – extending the approximation to larger $\mathbf{z}$

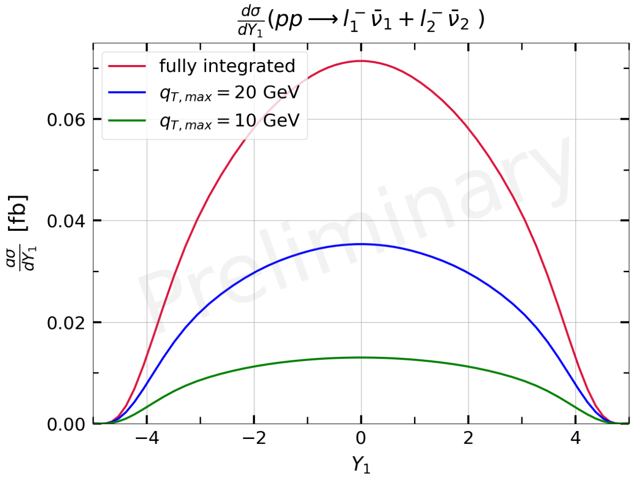


- Small $\mathbf{z}$ $\rightarrow$ interpolate between two approximations in the overlap region.
- $|\mathbf{y}| > y_{\max} \implies$ match DTMD at regularized distances $\mathbf{z}^*$, multiply by $e^{-\text{const.}\times\mathbf{z}_i^2}$.
- At small y extrapolate the short-distance result. Interpolate for intermediate $\mathbf{y}$.

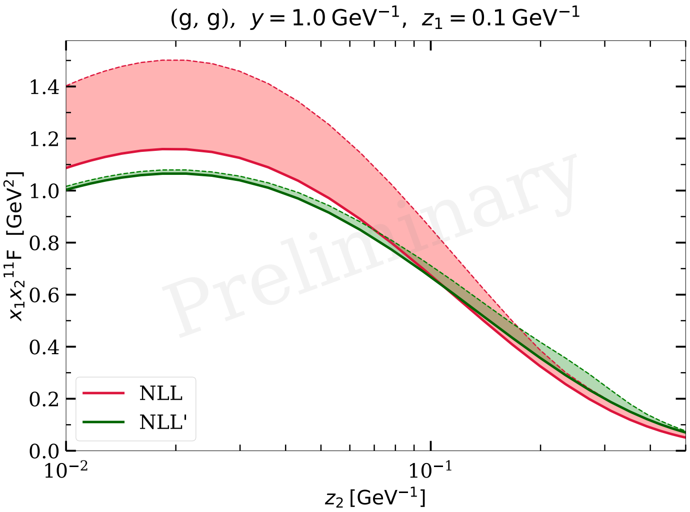
Backup – rapidity dependence for W^+W^+.



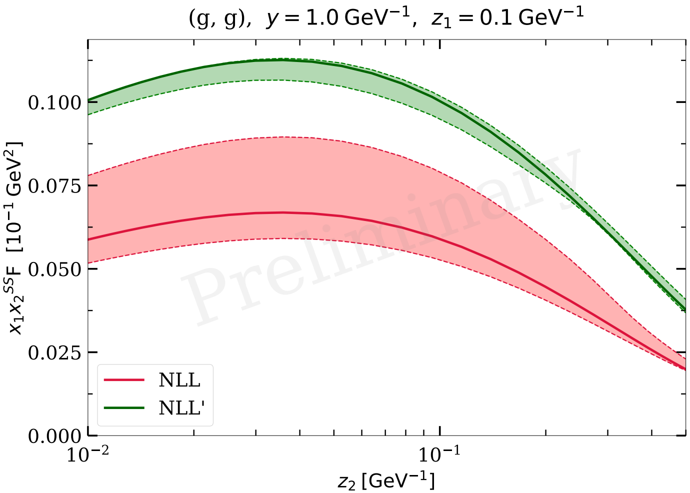
Backup – rapidity dependence for W^-W^-.



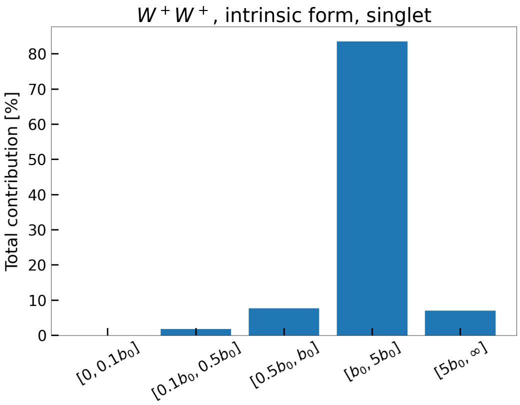
Backup – gluon DTMDs – $(R_1, R_2) = (1, 1)$

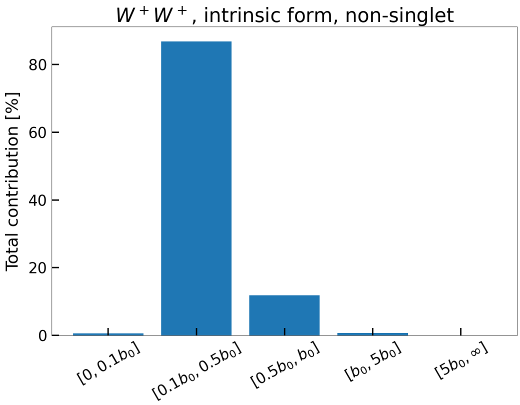


Backup – gluon DTMDs – $(R_1, R_2) = (S, S)$

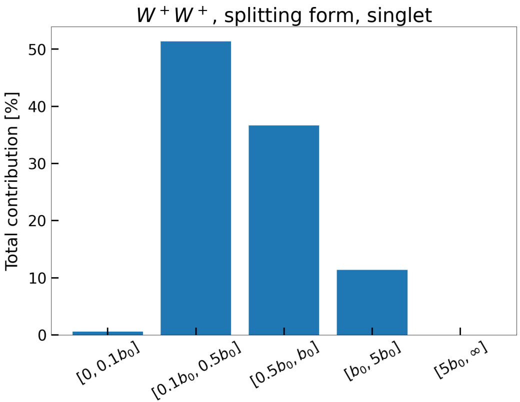


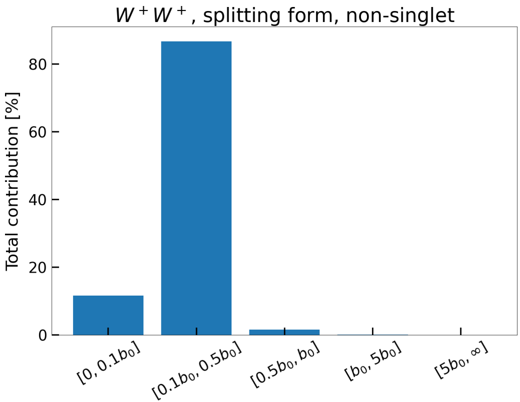
Backup – different y-regions for both color channels, intrinsic



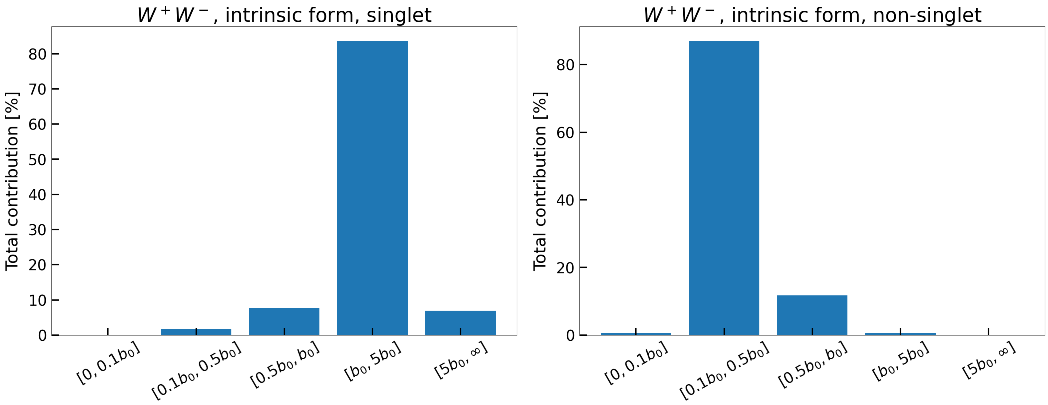


Backup – different y-regions for both color channels, splitting





Backup – different y-regions for both color channels, opposite-sign W



Backup – different y-regions for both color channels, opposite-sign W