Double parton scattering: collinear and TMD factorization

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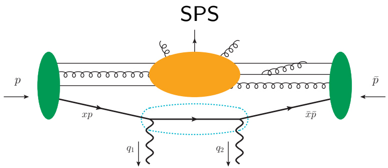
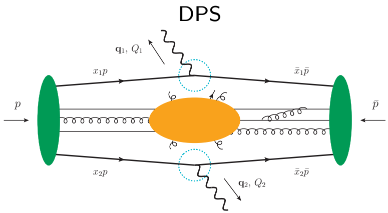
What is double parton scattering?



$$|\mathbf{q}_1^{\perp} + \mathbf{q}_2^{\perp}| \sim \Lambda \ll Q$$



$$|\mathbf{q}_1^{\perp}| \sim \Lambda \ll Q$$
$$|\mathbf{q}_2^{\perp}| \sim \Lambda \ll Q$$

Definition

Double parton scattering (DPS) is a proton-proton scattering process in which two partons from each proton undergo **two separate hard interactions**.

First appearance in theory studies:
Politzer Nucl. Phys. B172 (1980) 349
Paver, Treleani Nuovo Cim. A70 (1982) 215
Mekhfi Phys. Rev. D32 (1985) 2371

Other ground-setting works:
Gaunt, Stirling JHEP 03 (2010) 005
Blok et al. Eur. Phys. J. C72 (2012) 1963
Diehl et al. JHEP 03 (2012) 089
Manohar, Waalewijn Phys. Rev. D85 (2012) 114009
Ryskin, Snigierev Phys. Rev. D86 (2012) 014018
...

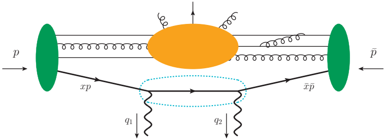
hard scale is $Q \sim \min(Q_1, Q_2)$

transverse-momenta scale is Λ

with $\Lambda_{\text{QCD}} \ll \Lambda \ll Q$

What is double parton scattering?

SPS



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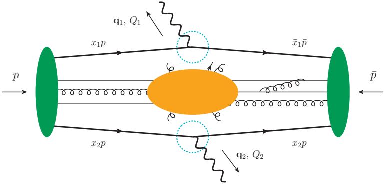
DPS



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Size comparison to SPS

- integrated XS: $\dfrac{\sigma_{\text{DPS}}}{\sigma_{\text{SPS}}} \sim \mathcal{O}\left(\dfrac{\Lambda^2}{Q^2}\right)$
  $\Longrightarrow$ phase-space suppressed
- differential XS:
  $$\frac{d^2\sigma_{\text{SPS}}}{d^2q_1\, d^2q_2} \sim \frac{d^2\sigma_{\text{DPS}}}{d^2q_1\, d^2q_2}$$
  $\Longrightarrow$ same power counting!

hard scale is $Q \sim \min(Q_1, Q_2)$

transverse-momenta scale is Λ

with $\Lambda_{\text{QCD}} \ll \Lambda \ll Q$

When is DPS important?

Where DPS is enhanced

- generally, DPS relevance increases with **collision energy**
- competitive with SPS in regions of **small** $|\mathbf{q}_1^\perp|, |\mathbf{q}_2^\perp|$
  $\rightarrow$ e.g. two pairs of back-to-back jets
- enhanced by parton luminosities at **small-x**, e.g. $F_{gg} \propto (f_g)^2$
- DPS dominant contribution for **coupling-suppressed processes** in SPS
  $\rightarrow$ same-sign WW production at $\mathcal{O}(\alpha_s^2)$ in SPS, but $\mathcal{O}(1)$ in DPS

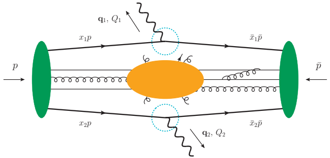
Peculiarities of DPS

- **polarization** gains importance, since an unpolarized proton can contain two polarized partons
- **color non-singlet** distributions enter the cross section even for color singlet final states
- need to account for the **overlap of single and double parton scattering**

DPS cross section

For colorless final states, an analogous factorized form to the SPS case can be derived

- $\hat{\sigma}^{(i)}$ are regular partonic cross sections
- F_{ab} are double parton distributions (DPDs)
- y [GeV^{-1}] is inter-parton transverse separation



here neglecting color indices and $x_i, \bar{x}_i$ dependence in the functions

C is a symmetry factor

Transverse-momentum dependent (TMD) factorization:

$$\frac{d\sigma_{\text{DPS}}}{dq_1^\perp \, dq_2^\perp} = \frac{1}{C} \sum_{a_1 a_2 b_1 b_2} \hat{\sigma}^{(1)}_{a_1 b_1} \, \hat{\sigma}^{(2)}_{a_2 b_2}$$

$$\times \int d^2 y \, \frac{d^2 z_1}{2\pi^2} \, \frac{d^2 z_2}{2\pi^2} \, e^{-iq_1^\perp z_1 - iq_2^\perp z_2} \, F_{a_1 a_2}(z_1, z_2, y) \, F_{b_1 b_2}(z_1, z_2, y)$$

In TMD factorization, $F_{ab}(z_1, z_2, y)$ are the TMDDPDs in position space.

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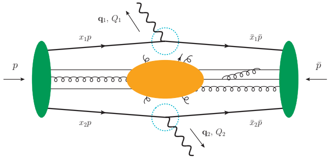

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C is a symmetry factor

Collinear factorization:

$$d\sigma_{\text{DPS}} = \frac{1}{C} \sum_{a_1 a_2 b_1 b_2} \hat{\sigma}^{(1)}_{a_1 b_1} \otimes \hat{\sigma}^{(2)}_{a_2 b_2} \otimes \int d^2 y \, F_{a_1 a_2}(y) \otimes F_{b_1 b_2}(y)$$

In collinear factorization, $F_{ab}(y)$ are the collinear DPDs in position space.

Assuming no inter-partonic correlations whatsoever, obtain convenient XS formula (the **DPS pocket formula**)

$$\sigma_{\text{DPS}} = \frac{1}{C} \frac{\sigma_1^{\text{SPS}} \sigma_2^{\text{SPS}}}{\sigma_{\text{eff}}}$$

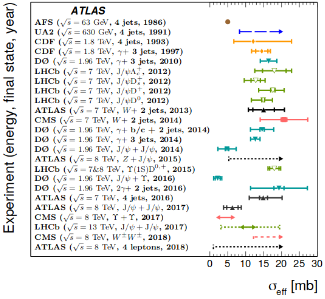
σ_{eff} used as a "measure" of DPS in exp's

Experimental searches

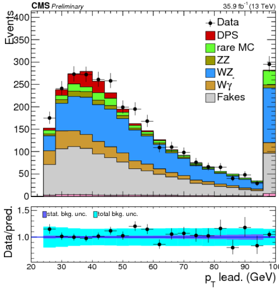
DPS observed since the '80s (4 jets, γ+3 jets, etc)

typical observables: WW, WJ/Ψ, $J/\Psi J/\Psi$, W+jets, ZZ, ...

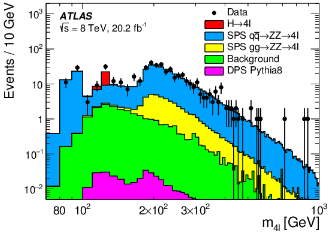
σ_{eff} measurements [CERN-EP-2018-274]



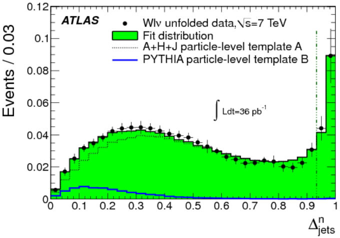
like-sign WW [CMS-PAS-FSQ-16-009]



4ℓ final state [CERN-EP-2018-274]



W + 2 jets [CERN-PH-EP-2012-355]



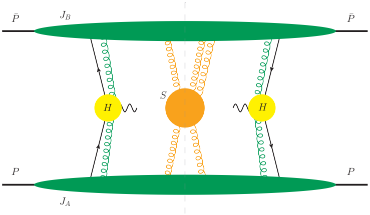
Status of factorization

A **formal all-order proof** of the factorization formulae in perturbative QCD **has been achieved for DPS** in the case of a **colorless final state**, both for the TMD and the collinear case. Current status is at the **same level as for the SPS** counterpart.

Diehl et al. JHEP 03 (2012) 089, JHEP 01 (2016) 076
Vladimirov JHEP 04 (2018) 045
Buffing et al. JHEP 01 (2018) 044
Diehl, RN JHEP 04 (2019) 124

The factorization procedure can be understood visually using cut diagrams:

SPS TMD factorization



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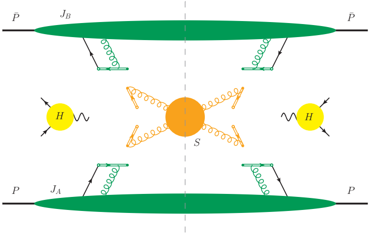

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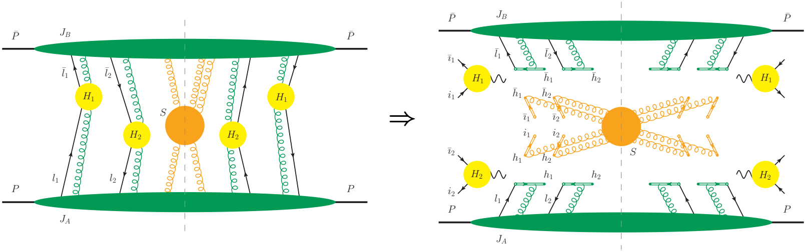
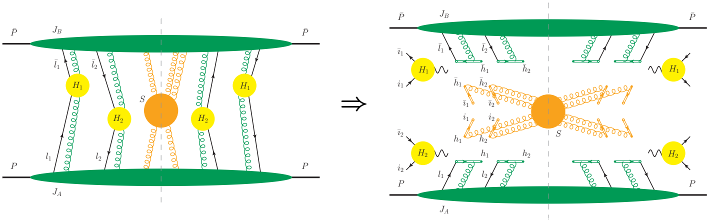


Structure of the proof

The all-order **factorization proof for DPS** generalizes the proofs by **Collins, Soper, Sterman** (CSS). It suffices to prove the TMD factorization; collinear factorization can be derived by integration of the TMD formula.

Sketch:

1. define a **power counting**, identify **leading regions** & introduce **kinematical approximations** Diehl, Ostermeier, Schäfer JHEP 03 (2012) 089
2. loops have to be cut: establish a **subtraction** mechanism Collins "Foundations of pQCD" (2011)
3. decouple **collinear gluons** from the hard interactions CSS Nucl.Phys.B261 (1985) 104
4. show factorization of **Glauber gluons** Diehl et al. JHEP 01 (2016) 076
5. factorize **soft gluons** from collinear graphs Diehl, RN JHEP 04 (2019) 124
6. obtain renormalized **operator definitions** of soft & collinear factors Diehl, Ostermeier, Schäfer JHEP 03 (2012) 089



Soft & collinear approximations

using light-cone coordinates $a \equiv (a^+, a^-, \vec{a})$
with $a^\pm = (a^0 \pm a^3)/\sqrt{2}$

Define scaling of momenta $\ell = (\ell^+, \ell^-, |\ell|)$

- hard: (Q, Q, Q)
- right-collinear: $\left(Q, \frac{\Lambda^2}{Q}, \Lambda\right)$; left-collinear: $\left(\frac{\Lambda^2}{Q}, Q, \Lambda\right)$
- central or ultra soft: $(\Lambda, \Lambda, \Lambda)$ or $\left(\frac{\Lambda^2}{Q}, \frac{\Lambda^2}{Q}, \frac{\Lambda^2}{Q}\right)$
- Glauber soft (bad): $\left(\Lambda, \frac{\Lambda^2}{Q}, \Lambda\right)$ or $\left(\frac{\Lambda^2}{Q}, \Lambda, \Lambda\right)$

Approximation example

At leading power:

- collinear gluons:
  $\ell_c^R = (\ell^+, 0, 0)$
  $\ell_c^L = (0, \ell^-, 0)$
- soft gluons:
  $\ell_s^R = (0, \ell^-, \vec{\ell})$
  $\ell_s^L = (\ell^+, 0, \vec{\ell})$

NOTE: in DPS must keep soft trans. momenta!

Grammer–Yennie approximation

Grammer, Yennie Phys. Rev. D8 (1973) 4332

In soft-to-collinear gluon propagators:

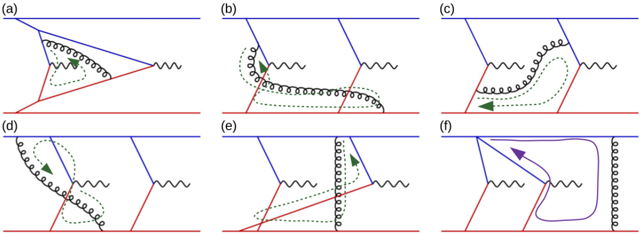
$$g^{\mu\nu} \to \frac{v^\mu \ell_s^\nu}{\ell \cdot v + i\epsilon}, \qquad (v \text{ aux. vector})$$

example: $S_\mu(\ell)\, J_A^\mu(\ell_s) \simeq S_\mu(\ell) \frac{v^\mu \ell_s^\nu}{\ell \cdot v + i\epsilon} J_{A\nu}(\ell_s)$

Combinations of **Grammer–Yennie factors** usually result in the appearance of **Wilson lines**.

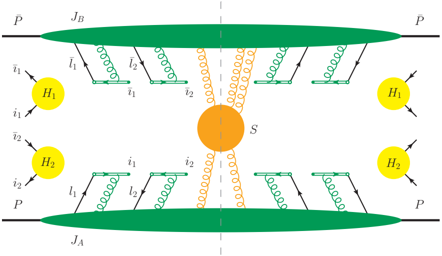
Glauber gluons cancellation

- The Grammer–Yennie approximation is not valid in the **Glauber region**, hence we must find a way to avoid this region.
- Glauber cancellation does not depend on the color structure, but only on the **kinematics** and **topology**.
- After checking all possible cases, **only non-trivial case** connects spectators before final state cut (see figure).
- Cancellation analogous to the one in SPS, i.e. due to **unitarity** (sum over final states at the cut).



from Diehl et al. proc. MPI@LHC 2015, 91-95

Factorization of collinear gluons from hard subgraphs



$$H_1 H_2 \quad \mathcal{L}_{XYZ} \quad | \quad \mathcal{L}^*_{XYZ} \quad H_1^* H_2^*$$

Collinear gluons factorize exactly like in SPS case

In amplitudes, substitute:

- $q_i(x) \to W_{ij}(x,v)\, q_j(x)$
- $\bar{q}_i(x) \to \bar{q}_j(x)\, W^\dagger_{ji}(x,v)$

X and Y are final-state cut of J_A and J_B

Z is final-state cut of S

After collinear gluons are factorized from the hard subgraphs:

$$\mathcal{L}_{XYZ}^{i_1 i_2\, \bar{\imath}_1 \bar{\imath}_2\, (n,\bar{n})}(q_1, q_2) = \frac{1}{n!\,\bar{n}!} \int [\text{hard momenta } l_m,\, \bar{l}_m] \int [\text{soft momenta } \ell_k,\, \bar{\ell}_k]$$
$$\times\, (2\pi)^4\, \delta^{(4)}\left(q_1 - l_1 - \bar{l}_1\right)\, (2\pi)^4\, \delta^{(4)}\left(q_2 - l_2 - \bar{l}_2\right) \left[J_{AX}^{i_1 i_2}(l_1, l_2; \{\tilde{\ell}_n\})\right]^{a_1 \ldots a_n}_{\mu_1 \ldots \mu_n}$$
$$\times \left[S_Z(\{\ell_n\}, \{\bar{\ell}_{\bar{n}}\})\right]^{\mu_1 \ldots \mu_n,\, \nu_1 \ldots \nu_{\bar{n}}}_{a_1 \ldots a_n,\, b_1 \ldots b_{\bar{n}}} \left[J_{BY}^{\bar{\imath}_1 \bar{\imath}_2}(\bar{l}_1, \bar{l}_2; \{\tilde{\bar{\ell}}_{\bar{n}}\})\right]^{b_1 \ldots b_{\bar{n}}}_{\nu_1 \ldots \nu_{\bar{n}}},$$

Ward identities

Many Grammer-Yennie factors produce Lorentz-contracted expressions:

$$\ell_1^{\mu_1} \dots \ell_n^{\mu_n} \left[J_{AX}^{i_1 i_2}(l_1, l_2; \{\ell_n\}) \right]_{\mu_1 \dots \mu_n}^{a_1 \dots a_n}$$

Apply **Ward identity** for an amplitude with n external gauge bosons $A_{\mu_i}(\ell_i)$

$$\ell_1^{\mu_1} \dots \ell_n^{\mu_n} \langle 0 | \dots A_{\mu_1}(\ell_1) \dots A_{\mu_n}(\ell_n) \dots | 0 \rangle = 0$$

with all momenta contracted, and **order-by-order** ('t Hooft, Veltman).

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$$\mathcal{L}_{XYZ}^{i_1 i_2 \bar{\imath}_1 \bar{\imath}_2 \, (n, \bar{n})} = \int [\text{F.T. on } \vec{\xi}_m] \int [\text{F.T. on } \vec{l}_m, \, l_m^-]$$

$$\times \, S_{Z \, h_1 h_2 \bar{h}_1 \bar{h}_2}(\vec{\xi}_m)$$

$$\times \, J_{AX}^{h_1 h_2}(l_1, l_2) \Big|_{l_1^+ = q_1^+, \, l_2^+ = q_2^+}$$

$$\times \, J_{BY}^{\bar{h}_1 \bar{h}_2}(\bar{l}_1, \bar{l}_2) \Big|_{\bar{l}_1^- = q_1^-, \, \bar{l}_2^+ = q_2^-}$$

- one soft factor S is decoupled
- two collinear factors $J_{A,B}$ $\rightarrow$ DPDs

Ward identities

Many Grammer-Yennie factors produce Lorentz-contracted expressions:

$$\ell_1^{\mu_1} \dots \ell_n^{\mu_n} \left[J_{AX}^{i_1 i_2}(l_1, l_2; \{\ell_n\}) \right]^{a_1 \dots a_n}_{\mu_1 \dots \mu_n}$$

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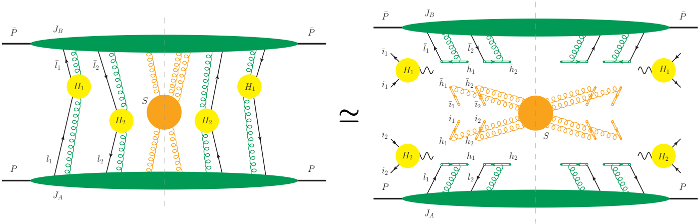
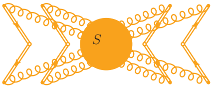


Soft factor

Buffing et al. JHEP 01 (2018) 044
Vladimirov JHEP 12 (2016) 038

The soft factor has a few properties:

- **hermitian in color space**: $S_{a_1 a_2} = S^\dagger_{a_1 a_2}$
- **hermitian in rep. space**: ${}^{RR'}S_{a_1 a_2} = ({}^{R'R}S_{a_1 a_2})^*$



TMD factorization

$$J_B{}^c\, S^{cd}\, J_A{}^d$$

In SPS and DPS, the soft factor depends on the color structure and on the Wilson-lines rapidity $y = \log \frac{v^+}{v^-}$

↓

Collins-Soper equation:

$$\frac{\partial}{\partial y} S(y) = K\, S(y)$$

collinear factorization

$$J_B{}^c\, S^{cd,ef}\, J_A{}^d\, H_1{}^e\, H_2{}^f$$

In SPS, integration over transverse momenta implies $S_q = 1$.

In DPS, ${}^{RR'}S_{a_1 a_2} \propto \delta_{RR'}$, color singlet ${}^{11}S_{qq} = 1$, but color non-singlets like ${}^{88}S_{qq}$ depend on rapidity (however Sudakov suppressed).

At NNLO, S can be expressed completely in terms of SPS TMD soft factor

Double parton distributions

more detail in next talk by Peter Plößl

"Bare" TMD DPDs

From factorization formula, definition of "bare" DPDs is similar to PDFs

$$F^{(0)}_{a_1 a_2}(x_1, x_2, z_1, z_2, y) \propto \langle p| \, \mathcal{O}_{a_1}(y, z_1) \, \mathcal{O}_{a_2}(0, z_2) \, |p\rangle \, \Big|_{z_i^+ = y_i^+ = 0}$$

in terms of operators $\mathcal{O}(y, z) \sim \bar{\psi}(y - \frac{1}{2} z) \, \Gamma \, \psi(y + \frac{1}{2} z)$.

"Bare" collinear DPDs

Collinear DPDs are obtained from TMD DPDs:

- position-space DPDs $F^{(0)}_{a_1 a_2}(x_1, x_2, y)$ by letting $z_1, z_2 \to 0$
  - ↪ appear in cross section
- momentum-space DPDs $F^{(0)}_{a_1 a_2}(x_1, x_2, \Delta)$ by Fourier transform
  - ↪ appear in DPD sum rules

Renormalized collinear DPDs

- position-space DPDs $F_{a_1 a_2}(x_1, x_2, y, \mu_1, \mu_2)$ obey **double DGLAP equations**
  - ↪ evolution and flavor matching up to NNLO available with **ChiliPDF**
- momentum-space DPDs $F_{a_1 a_2}(x_1, x_2, \Delta, \mu_1, \mu_2)$ obey **inhomogeneous generalized DGLAP equations**
  - ↪ numerically solved by Gaunt, Stirling JHEP 03 (2010) 005

DPDs from perturbative splitting

At present, DPDs cannot be extracted from exp's $\longrightarrow$ Ansatz necessary

A class of DPD Ansätze at small y

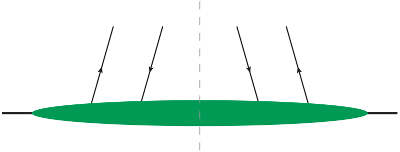
From OPE, at small y DPDs are sum of "**intrinsic**" and "**splitting**" piece

$$F(y) = F_{\text{int}}(y) + F_{\text{spl}}(y)$$

At large y DPDs can be modeled so that $\lim_{y\to\infty} F(y) = 0$.

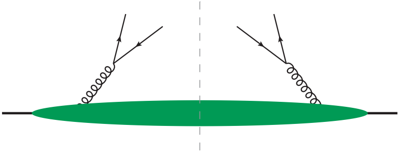
Perturbative splitting

- from MEs: $F_{\text{spl}}(y) \propto \dfrac{1}{y^2}$
- UV divergence in cross-section
$$\int \mathrm{d}^2 y \, F_1 \, F_2 \sim \int \frac{\mathrm{d}^2 y}{y^4}$$
- reason: region of overlap between SPS and DPS



intrinsic (F_{int} or "2")

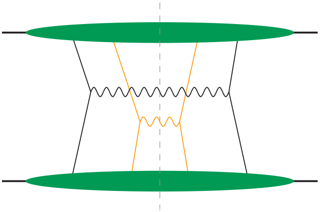
twist-4 distribution at small y, nonperturbative



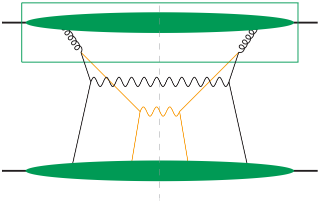
perturbative splitting (F_{spl} or "1")

- LO: $F_{ab} \propto P_{a_0 \to ab} \cdot f_{a_0}$
  Diehl et al. JHEP 03 (2012) 089
- NLO: computed, also color non-singlet
  Diehl et al. SciPost Phys. 7 (2019) 017
  Diehl et al. JHEP 08 (2021) 040

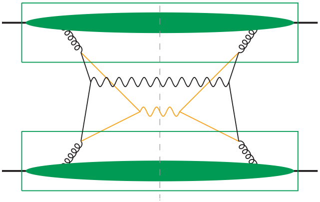
Interplay of splitting and intrinsic contributions



2v2 $\longrightarrow$ not divergent



2v1 $\longrightarrow$ divergence is $\frac{\mathbf{d}^2 \boldsymbol{y}}{\boldsymbol{y}^2} \longrightarrow \mathbf{log}\, \boldsymbol{y}$ terms

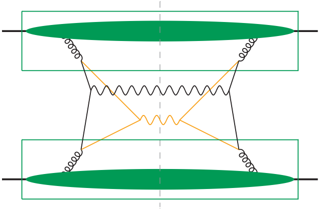


1v1 $\longrightarrow$ divergence is $\frac{\mathbf{d}^2 \boldsymbol{y}}{\boldsymbol{y}^4}$, must be subtracted

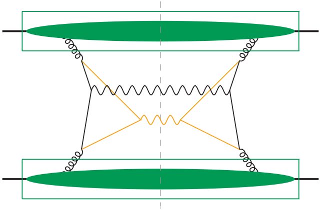
Double-counting between SPS and DPS

The UV divergence in $\boldsymbol{y}$ is associated to the **double counting of SPS and DPS** contributions in the region where $\boldsymbol{y} \to \mathbf{0}$:

DPS interpretation (1v1)



SPS interpretation



Double-counting between SPS and DPS

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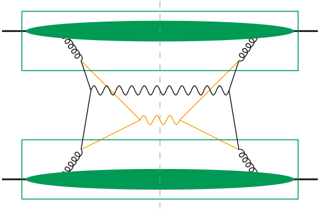

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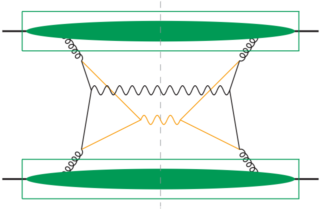

Solution: DGS scheme

The DGS subtraction scheme cancels the UV divergence at all orders:

$$\boxed{\sigma = \sigma_{\text{SPS}} + \sigma_{\text{DPS}} - \sigma_{\text{sub}}}\,, \qquad \sigma_{\text{sub}} = \sigma_{\text{DPS}} \text{ with } F_{1,2} = F_{\text{spl}}$$

where the DPS cross section is regularized introducing a cutoff $\nu \sim Q$

$$\sigma_{\text{DPS}} \propto \int \mathrm{d}^2 y\, F_1(y)\, F_2(y) \to \int \mathrm{d}^2 y\, \Phi^2(y\nu)\, F_1(y)\, F_2(y)$$

Simple cutoff regulator $\Phi(y\nu) = \Theta(y\nu - 2e^{-\gamma_E})$.

Diehl, Gaunt, Schönwald JHEP 06 (2017) 083

State of the art

Recent theory developments

- `dShower`: a **parton shower** combining SPS and DPS, implementing the "$\mathbf{1 \to 2}$" splitting and treating the SPS-DPS double counting

  Cabouat, Gaunt JHEP 10 (2020) 012

- **lattice QCD**: extracted moments of the pion DPD and of the proton DPD

  Bali et al. JHEP 02 (2021) 067, JHEP 09 (2021) 106

- a lot **more insight on DPDs**: evolution, sum rules, NLO splitting, color non-singlet distributions   Diehl et al. SciPost Phys. 7 (2019) 2, 017, Eur.Phys.J.C 80 (2020) 5, 468, JHEP 08 (2021) 040, arXiv:2109.14304

DPS phenomenology

- DPD models

  ↪ constituent quark models (Rinaldi, Scopetta, Ceccopieri), "bag" model (Manohar, Waalewijn) valence quark models (Broniowski, Ruiz Arriola), KMR approach (Golec-Biernat, Staśto), . . .

- multitude of phenomenological studies that include DPS

  Blok, Dokshitzer, Frankfurt, Strikman, Maciuła, Szczurek, Kutak, van Hameren, Gaunt, Kom, Kulesza, Stirling, Fedkyevich, Kasemets, Myska, Cotogno, Lansberg, Yamanaka, Zhang, Shao, Ceccopieri, Rinaldi, Scopetta, ...

- DPS in pA collisions and TPS (triple parton scattering) D'Enterria, Snigirev

Summary

- **DPS** contributions can be **comparable or even dominant** w.r.t. SPS in some cases
- status of DPS **factorization proofs** is at the same level as for SPS
- **double-counting** of SPS and DPS in small-y region is understood
- double **DGLAP evolution** and flavor matching are under control thanks to developments of new tools
- perturbative **splitting** form of DPDs known **up to NLO**, also for color non-singlet distributions
- a **DPS parton shower** is being developed

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Thank you!

The latest extractions of σ_{eff}

latest measurements (CMS, 4-jets at 13 TeV) [CMS-PAS-SMP-20-007]