Double parton scattering

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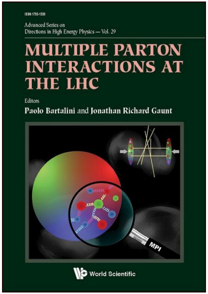
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Scope of this talk

- double parton scattering: general introduction
  and a selection of recent results
- focus on theory and phenomenology
  more on experiment: talk by M. Pieters, Thursday 16:30

For more information see e.g.

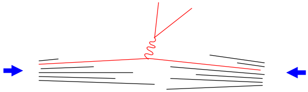
- most recent workshop on MPI@LHC:
  https://indico.cern.ch/event/736470
- Multiple parton interactions at the LHC
  eds. P. Bartalini and J. R. Gaunt, December 2018
  individual chapters available on arXiv



Hadron-hadron collisions

- standard description based on factorisation formulae

  cross sect = parton distributions × parton-level cross sect



- factorisation formulae are for inclusive cross sections $pp \to A + X$
  where $A =$ produced by parton-level scattering, specified in detail
  $X =$ summed over, no questions asked

Hadron-hadron collisions

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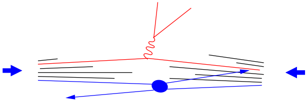
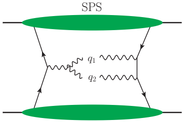
  cross sect = parton distributions × parton-level cross sect



- factorisation formulae are for inclusive cross sections $pp \to A + X$
  where $A =$ produced by parton-level scattering, specified in detail
  $X =$ summed over, no questions asked
- spectator interactions
  - cancel in inclusive cross sections thanks to unitarity
  - can be soft $\rightsquigarrow$ part of underlying event
  - or hard $\rightsquigarrow$ multiple hard scattering
- double parton scattering $pp \to A_1 + A_2 + X$ with scales $Q_1, Q_2 \gg \Lambda$
  - have factorisation formula with double parton distributions
  - if $Q_1 \gg Q_2 \gg \Lambda$ $\rightsquigarrow$ part of underlying event for $pp \to A_1 + X$

Single vs. double parton scattering (SPS vs. DPS)

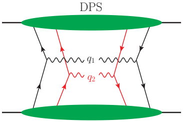
- example: two e.w. gauge bosons with transverse momenta $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$



single scattering:

$|\boldsymbol{q}_1|$ and $|\boldsymbol{q}_2| \sim Q = Q_1 = Q_2$

$|\boldsymbol{q}_1 + \boldsymbol{q}_2| \ll Q$



double scattering:

both $|\boldsymbol{q}_1|$ and $|\boldsymbol{q}_2| \ll Q$

- for transv. momenta $\sim \Lambda \ll Q$:

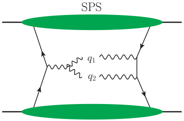
$$\frac{d\sigma_{\text{SPS}}}{d^2\boldsymbol{q}_1\, d^2\boldsymbol{q}_2} \sim \frac{d\sigma_{\text{DPS}}}{d^2\boldsymbol{q}_1\, d^2\boldsymbol{q}_2} \sim \frac{1}{Q^4\,\Lambda^2}$$

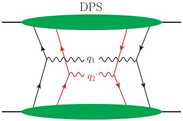
but single scattering populates larger phase space :

$$\sigma_{\text{SPS}} \sim \frac{1}{Q^2} \gg \sigma_{\text{DPS}} \sim \frac{\Lambda^2}{Q^4}$$

Single vs. double parton scattering (SPS vs. DPS)

- example: two e.w. gauge bosons with transverse momenta $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$





single scattering:

$|\boldsymbol{q}_1|$ and $|\boldsymbol{q}_2| \sim Q = Q_1 = Q_2$

$|\boldsymbol{q}_1 + \boldsymbol{q}_2| \ll Q$

double scattering:

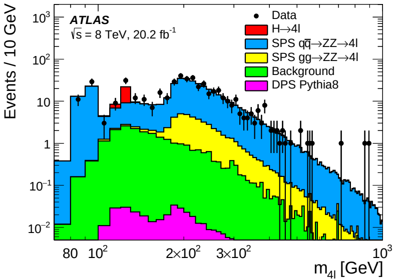
both $|\boldsymbol{q}_1|$ and $|\boldsymbol{q}_2| \ll Q$

- DPS contribution may matter for precision analyses, e.g.
  - TGC measurements in W^+W^- production
  - Higgs decays into $ZZ^* \to 4$ leptons

Four lepton production

ATLAS, arXiv:1811.11094, PLB 790 (2019) 595

- ATLAS analysis using $20.2\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$
- four leptons $\ell_1^+ \ell_1^- \, \ell_2^+ \ell_2^-$ with $\ell_{1,2} = e, \mu$
- event selection in invariant mass range $80\,\mathrm{GeV} \le m_{4\ell} \le 1000\,\mathrm{GeV}$
  find 476 events

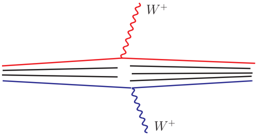


- neural network to discriminate between DPS and SPS
- DPS simulated by PYTHIA8
- no significant signal found
  upper limit on DPS fraction:

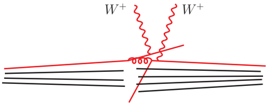
$$f_{\mathrm{DPS}} < 0.042 \quad @\ 95\%\ \mathrm{CL}$$

Like-sign W pairs

$\sigma_{\text{DPS}} \propto \mathcal{O}(\alpha_s^0)$



$\sigma_{\text{SPS}} \propto \mathcal{O}(\alpha_s^2)$ with ≥ 2 jets



- with leptonic W decays get light-sign lepton pairs and missing E_T
- this is also a search channel for new physics
  (e.g. supersymmetry, top partners)
- several theory studies
  Kulesza, Stirling 1999; Gaunt, Kom, Kulesza, Stirling 2003;
  Ceccopieri, Rinaldi, Scopetta 2017; Cotogno, Kasemets, Myska 2018

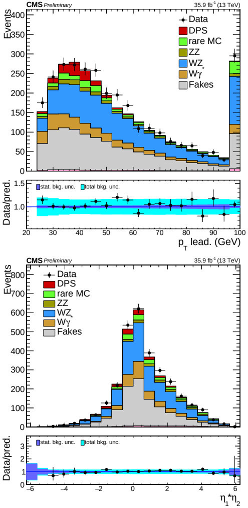
Like-sign W pairs

CMS-PAS-FSQ-16-009

- CMS analysis with $35.9\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
- two like-sign leptons $\mu^{\pm}\mu^{\pm}$ or $\mu^{\pm}e^{\pm}$
- event selection includes $N_{\text{jets}} < 2$ and $N_{b\text{-jets}} = 0$
  find 2975 events with 2 leptons
- multivariate analysis with 11 variables
  shown in r.h.s. plots are
  - p_T of leading lepton
  - product $\eta_1 \cdot \eta_2$ of lepton pseudorapidities

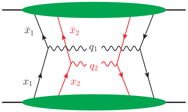
  DPS simulated by `PYTHIA8`
- obtain

$$\sigma^{WW}_{\text{DPS}} = 1.09^{+0.50}_{-0.49}\,\mathrm{pb}$$



analysis with $19.7\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ gave $\sigma^{WW}_{\text{DPS}} < 1.12\,\mathrm{pb}$ CMS-PAS-FSQ-13-001

DPS cross section: simple theory



$$\frac{d\sigma_{\text{DPS}}^{A_1 A_2}}{dx_1\, d\bar{x}_1\; dx_2\, d\bar{x}_2} = \frac{1}{1+\delta_{A_1 A_2}}\, \hat{\sigma}_1\, \hat{\sigma}_2 \int d^2\boldsymbol{y}\; F_{a_1 a_2}(x_1, x_2, \boldsymbol{y})\, F_{\bar{a}_1 \bar{a}_2}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

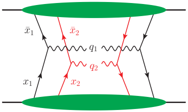
$\hat{\sigma}_i =$ parton-level cross section for $a_i + \bar{a}_i \to A_i$

$F_{a_1 a_2}(x_1, x_2, \boldsymbol{y}) =$ double parton distribution (DPD)

$\boldsymbol{y} =$ transv. distance between partons

- can extend $\hat{\sigma}_i$ to higher orders in α_s
  get usual convolution integrals over x_i in $\hat{\sigma}_i$ and F
- tree-level formula from Feynman graphs and kinematic approximations
  Paver, Treleani 1982, 1984; Mekhfi 1985, . . . , MD, Ostermeier, Schäfer 2011
- full factorisation proof for double Drell-Yan
  Vladimirov 2016, 2017; MD, Buffing, Gaunt, Kasemets, Nagar, Ostermeier, Plößl, Schäfer, Schönwald 2011–2018
  requires modification of above formula (more later)

DPS cross section: simple theory



$$\frac{d\sigma^{A_1 A_2}_{\text{DPS}}}{dx_1\, d\bar{x}_1\; dx_2\, d\bar{x}_2} = \frac{1}{1+\delta_{A_1 A_2}}\, \hat{\sigma}_1\, \hat{\sigma}_2 \int d^2\boldsymbol{y}\; F_{a_1 a_2}(x_1, x_2, \boldsymbol{y})\, F_{\bar{a}_1 \bar{a}_2}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

$\hat{\sigma}_i =$ parton-level cross section for $a_i + \bar{a}_i \to A_i$

$F_{a_1 a_2}(x_1, x_2, \boldsymbol{y}) =$ double parton distribution (DPD)

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- simplest assumption $F_{a_1 a_2}(x_1, x_2, \boldsymbol{y}) = f_{a_1}(x_1)\, f_{a_2}(x_2)\, G(\boldsymbol{y})$ gives

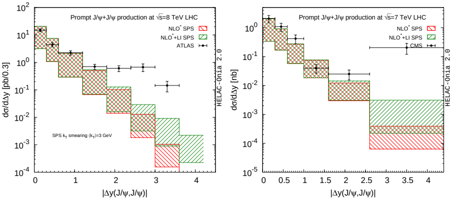
$$\sigma^{A_1 A_2}_{\text{DPS}} = \frac{1}{1+\delta_{A_1 A_2}}\, \frac{\sigma^{A_1}_{\text{SPS}}\, \sigma^{A_2}_{\text{SPS}}}{\sigma_{\text{eff}}} \qquad \text{with} \quad \frac{1}{\sigma_{\text{eff}}} = \int d^2\boldsymbol{y}\; G(\boldsymbol{y})^2$$

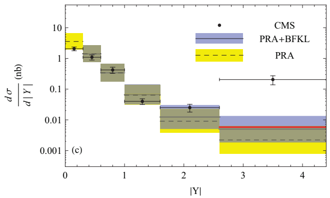
  - straightforward generalisation to N independent scatters underlies DPS and UE implementations in `PYTHIA` and `Herwig` with adjustments for conserving momentum and quark number
  - may approximately work in some situations and entirely fail in others

DPS in heavy quark production

- generic source of DPS enhancement over SPS: small parton x
  approx. $\sigma_{\text{SPS}} \propto f(x_1 + x_2)\, f(\bar{x}_1 + \bar{x}_2)$ vs. $\sigma_{\text{DPS}} \propto f(x_1)\, f(x_2)\, f(\bar{x}_1)\, f(\bar{x}_2)$
- DPS often enhanced at large $|\Delta Y|$ between A_1 and A_2
  in DPS: $2\Delta Y = \log(x_1 \bar{x}_2)/(\bar{x}_1 x_2)$
- several DPS measurements with heavy quarks at Tevatron and LHC:
  $J/\Psi\, J/\Psi$, DD, $J/\Psi\, D$, ΥD, ... review by Belyaev, Savrina 2017
  - small x and low hard scales enhance DPS
  - calculation of SPS tends to be difficult
- updated SPS calculations for double J/Ψ, including small-x effects

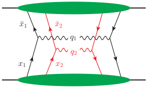
Lansberg, Shao, Yamanaka, Zhang 2019 He, Kniehl, Nefedov, Saleev 2019



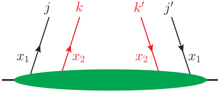


Double parton scattering: more theory

$$\frac{d\sigma_{\text{DPS}}}{dx_1\, d\bar{x}_1\, dx_2\, d\bar{x}_2} = \frac{\hat{\sigma}_1\, \hat{\sigma}_2}{1+\delta_{A_1 A_2}} \int d^2\boldsymbol{y}\; F(x_1, x_2, \boldsymbol{y})\, F(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$



- DPDs include correlations between partons in x_1, x_2 and $\boldsymbol{y}$
- must also include DPDs for correlations in parton
  - spin: e.g. difference between aligned and anti-aligned helicities
    $$q_1^{\uparrow} q_2^{\uparrow} + q_1^{\downarrow} q_2^{\downarrow} - q_1^{\uparrow} q_2^{\downarrow} - q_1^{\downarrow} q_2^{\uparrow}$$
    more later
  - colour: e.g. for quarks



colour of lines with momentum fraction x_i can be coupled to

- singlet: $\delta^{jj'}\delta^{kk'}$ as in ordinary PDFs
- octet: $t_a^{jj'}\, t_a^{kk'}$ not possible in PDFs

colour non-singlet combinations suppressed at high scales Q

Manohar, Waalewijn 2012

relevance at moderate Q ($\to$ underlying event) not well studied

Double parton scattering: more theory

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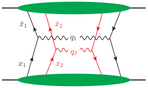
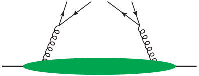


- for $|\boldsymbol{y}| \ll 1/\Lambda$ can compute

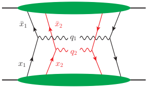
  $$F(x_1, x_2, \boldsymbol{y}) \sim \frac{1}{\boldsymbol{y}^2} \text{ splitting fct.} \otimes \text{usual PDF}$$



  first results at NLO $(\mathcal{O}(\alpha_s^2))$
  MD, Gaunt, Plößl, Schäfer 2019

Double parton scattering: more theory

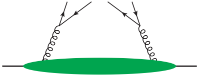
$$\frac{d\sigma_{\text{DPS}}}{dx_1\, d\bar{x}_1\, dx_2\, d\bar{x}_2} = \frac{\hat{\sigma}_1\, \hat{\sigma}_2}{1 + \delta_{A_1 A_2}} \int d^2\boldsymbol{y}\; F(x_1, x_2, \boldsymbol{y})\, F(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$



- for $|\boldsymbol{y}| \ll 1/\Lambda$ can compute

  $$F(x_1, x_2, \boldsymbol{y}) \sim \frac{1}{\boldsymbol{y}^2} \text{ splitting fct.} \otimes \text{usual PDF}$$

  gives UV divergent cross section $\propto \int d^2\boldsymbol{y}/\boldsymbol{y}^4$
  in fact, DPS formula only valid for $|\boldsymbol{y}| \gg 1/Q$



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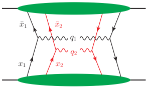

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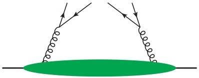
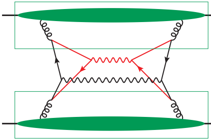
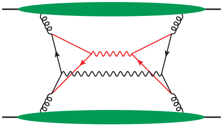


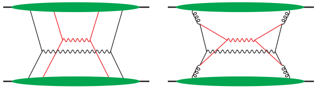
- have double counting problem between DPS with splitting and SPS at high-loop level (twisted box graphs)





MD, Ostermeier, Schäfer 2011; Gaunt, Stirling 2011; Gaunt 2012; Blok, Dokshitzer, Frankfurt, Strikman 2011; Ryskin, Snigirev 2011, 2012; Manohar, Waalewijn 2012; noticed by Cacciari, Salam, Sapeta 2009

Combining DPS with SPS

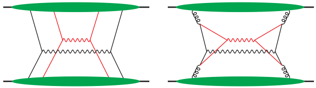


- how to delineate DPS and SPS is a matter of definition/scheme choice
  intuitively: large $|\boldsymbol{y}| \gg 1/Q$ is DPS, small $|\boldsymbol{y}| \sim 1/Q$ is SPS
- scheme worked out in MD, Gaunt, Schönwald 2017
  - introduce cutoff $|\boldsymbol{y}| > 1/\nu$ in σ_{DPS} (or a similar cutoff)
    choose scale $\nu \sim Q = \min(Q_1, Q_2)$ to resum large logarithms in DPS
  - full cross section:

$$\sigma = \sigma_{\text{DPS}} - \sigma_{\text{sub}} + \sigma_{\text{SPS}}$$

    double counting removed by σ_{sub}
    $= \sigma_{\text{DPS}}$ with F computed for small $\boldsymbol{y}$ in perturb. theory
  - σ_{SPS} defined as usual $\Rightarrow$ no new calculation needed
  - ν dependence cancels between σ_{DPS} and σ_{sub}

Combining DPS with SPS



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  - full cross section:

$$\sigma = \sigma_{\text{DPS}} - \sigma_{\text{sub}} + \sigma_{\text{SPS}}$$

  - use ν variation of σ_{DPS} as indicator:
    large variation $\Rightarrow$ dominated by $|\boldsymbol{y}| \sim 1/Q$
    $\Rightarrow$ corresponding order of SPS is important
    small variation $\Rightarrow$ dominated by $|\boldsymbol{y}| \gg 1/Q$
    $\Rightarrow$ DPS in perturbative splitting or nonperturbative regime
- other proposed treatments: Blok, Dokshitzer, Frankfurt, Strikman 2012, 2013; Ryskin, Snigirev 2011, 2012; Manohar, Waalewijn 2012

DGLAP evolution

- define DPDs as matrix elements of renormalised twist-two operators:

$$F(x_1, x_2, \boldsymbol{y}; \mu_1, \mu_2) \sim \langle p | \mathcal{O}_1(\mathbf{0}; \mu_1)\, \mathcal{O}_2(\boldsymbol{y}; \mu_2) | p \rangle$$

$$f(x; \mu) \sim \langle p | \mathcal{O}(\mathbf{0}; \mu) | p \rangle$$

  $\Rightarrow$ separate DGLAP evolution for partons 1 and 2:

$$\frac{\partial}{\partial \log \mu_i^2} F(x_1, x_2, \boldsymbol{y}; \mu_1, \mu_2) = P \underset{x_i}{\otimes} F \qquad \text{for } i = 1, 2$$

- allows for different hard scales μ_1, μ_2 (esp. useful for underlying event)
- numerical implementation challenging
  (many variables and parton combinations a_1, a_2)
  - different evolution codes used in Gaunt, Stirling 2010 and later work and Elias, Golec-Biernat, Staśto 2017
  - ongoing work $\rightarrow$ talk by R Nagar, Monday 16:55

slide provided by J. R. Gaunt

A Monte Carlo implementation of the DGS framework

Advantages of MC parton shower implementation: exclusive final states, can implement arbitrary cuts

DGS framework implemented as dShower: Cabouat, Gaunt, Ostrolenk, 2019

- Select kinematics of hard processes and parton separation y according to DGS DPS formula.
- Backward evolution from hard process using homogeneous double DGLAP equations:

$$d\mathcal{P}_{ij}^{\mathrm{ISR}} = d\mathcal{P}_{ij} \exp\left(-\int_{Q^2}^{Q_h^2} d\mathcal{P}_{ij}\right)$$

$$d\mathcal{P}_{ij} = \frac{dQ^2}{Q^2}\left(\sum_{i'}\int_{x_1}^{1-x_2}\frac{dx_1'}{x_1'}\frac{\alpha_s(p_\perp^2)}{2\pi}P_{i'\to i}\left(\frac{x_1}{x_1'}\right)\frac{F_{i'j}(x_1',x_2,\boldsymbol{y},Q^2)}{F_{ij}(x_1,x_2,\boldsymbol{y},Q^2)} + \sum_{j'}\int_{x_2}^{1-x_1}\frac{dx_2'}{x_2'}\frac{\alpha_s(p_\perp^2)}{2\pi}P_{j'\to j}\left(\frac{x_2}{x_2'}\right)\frac{F_{ij'}(x_1,x_2',\boldsymbol{y},Q^2)}{F_{ij}(x_1,x_2,\boldsymbol{y},Q^2)}\right)$$

'Guided' by some DPD set

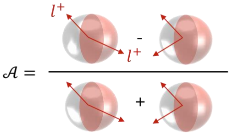
- $2 \to 1$ 'mergings' in backward evolution at scale $\mu_y \sim 1/y$, with probability given by splitting DPD/total DPD.

Some discussion of mergings ('joined interactions') given already in Sjöstrand, Skands, 2004, but here y-dependence of mergings taken into account.

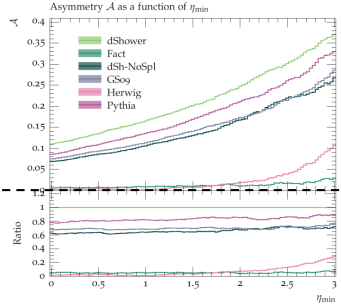
A Monte Carlo implementation of the DGS framework

First numerical investigation:

- same-sign WW $\qquad pp \to W^+W^+ \to e^+\nu_e\mu^+\nu_\mu$
- 3 quark flavours
- DPDs from DGS paper, with modifications to very approximately take account of number & momentum sum rule constraints Gaunt, Stirling, 2010, Blok, Dokshitzer, Frankfurt, Strikman, 2013, Ceccopieri, 2014, MD, Plößl, Schäfer, 2018



Gaunt, Kom, Kulesza, Stirling, 2010



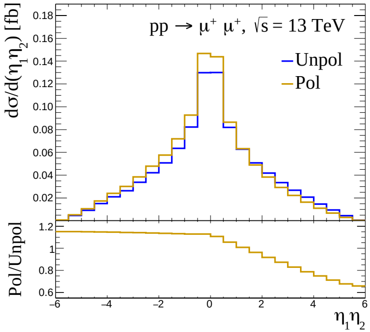
Includes 1→2 splittings + valence number effects

Simple valence number effects

No parton-parton correlations

Like-sign W pairs again

- sensitive to longitudinal parton spin correlations
  (partons 1 and 2 with same or opposite helicities)
- phenomenological study: Cotogno, Kasemets, Myska 2018
  including cuts and background estimates
- assume maximal spin correlation at low scale $\mu_0 = 1\,\mathrm{GeV}$, then evolve



- no parton correlations → symmetric distribution in product $\eta_1 \cdot \eta_2$ of lepton rapidities
- estimate that significant asymmetry can be observed at HL-LHC

Parton correlations: a lattice study

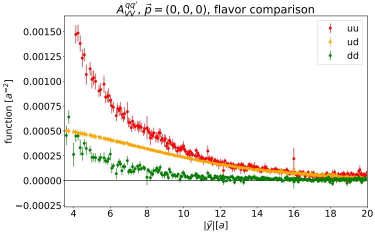
- correlation function of two local currents $\langle p| J_1^{\mu}(0)\, J_2^{\nu}(y) |p\rangle$ can be computed in lattice QCD (for spacelike distance $y^2 < 0$)
- is related with Mellin moment ($\int dx_1 dx_2$) of DPDs

MD, Ostermeier, Schäfer 2011

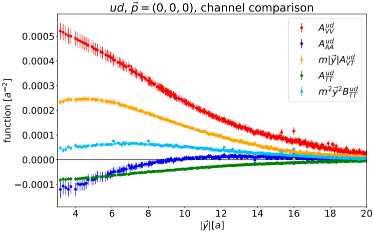
- preliminary results from a $32^3 \times 96$ lattice, $m_\pi \approx 360\,\mathrm{MeV}$, $a \approx 0.086\,\mathrm{fm}$

plots from: C Zimmerman, talk at Lattice 2019 (indico link)

correlation functions $A(y)$, $B(y)$ related with Mellin moments of DPDs



currents renormalised at $\mu = 2\,\mathrm{GeV}$



V: unpolarised, A: longitud. pol., T: transv. pol.

Recent results not covered here: a selection

- electroweak channels

  R. Kumar, M. Bansal, S. Bansal 2019: jet fragmentation for DPS in Z + dijets

- heavy flavour production

  H. S. Shao, Y. J. Zhang 2019: triple prompt J/Ψ production

  A. V. Karpishkov, M. A. Nefedov, V. A. Saleev 2019: ΥD production

  R. Maciula and A. Szczurek 2018: $D^0 B^+$ and $B^+ B^+$ production

- double parton distributions

  C. Mondal, A. Mukherjee, S. Nair 2019: DPDs in a positronium-like bound state

  M. Rinaldi, F. A. Ceccopieri 2018: transverse proton structure from DPDs

  M. Rinaldi, S. Scopetta, M. Traini, V. Vento 2018: DPDs in the pion

  E. Elias, K. Golec-Biernat, A. M. Staśto 2018: unintegrated gluon DPD

- proton-nucleus collisions

  I. Helenius, H. Paukkunen 2019: double D-meson production

  E. Huayra, E. G. De Oliveira, R. Pasechnik 2019: charm and bottom production

  M. Alvioli, M. Azarkin, B. Blok, M. Strikman 2019: minijet dynamics

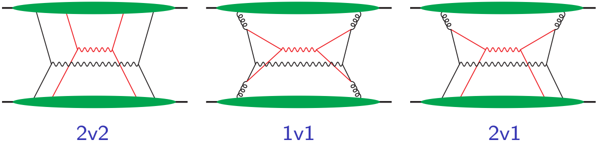
  O. Fedkyevich, talk at MPI@LHC 2019: 4 jets and 3 jets + γ production

Summary

- double parton scattering important
  in specific kinematics/for specific processes
  including hard part of underlying event
- many measurements from LHC Run I, first results from Run II
  start being sensitive to rare DPS processes
- recent years: progress towards systematic description in QCD
- UV problem of DPS $\leftrightarrow$ double counting with SPS
  $\rightsquigarrow$ must define distinction between DPS and SPS

  DGS scheme:
  - simple UV regulator for DPS (cutoff in distance y between partons)
  - simple subtraction term to avoid double counting
- ongoing work on a DPS parton shower (dShower)
- parton correlations can have observable effects if they are sufficiently large

Perturbative splitting in only one proton



- can have perturbative splitting in both protons (1v1), or just in one (2v1)
- dedicated studies of 2v1 mechanism
  find that numerical import in LHC processes
  Blok et al 2011-13, Blok, Gunnellini 2015; Gaunt 2012
- overlaps with contribution with one twist 2 and one twist 4 distribution
  is fully incorporated in DGS formalism