Multiparton interactions in pp collisions: between bug and feature

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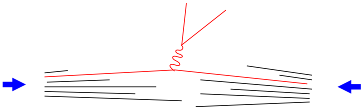
Hadron-hadron collisions

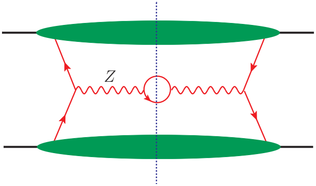
- standard description based on factorization formulae

  cross sect = parton distributions × parton-level cross sect

  example: Z production

  $$pp \to Z + X \to \ell^+\ell^- + X$$





- factorization formulae are for inclusive cross sections $pp \to Y + X$
  where Y = produced in parton-level scattering, specified in detail
  X = summed over, no details

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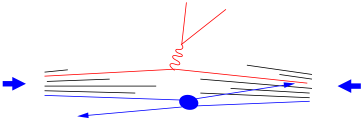
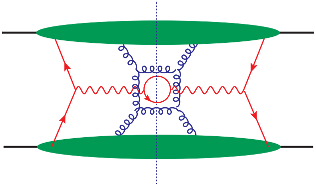
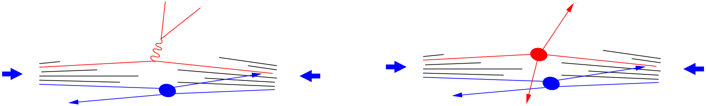




- factorization formulae are for inclusive cross sections $pp \to Y + X$
  where $Y =$ produced in parton-level scattering, specified in detail
  $X =$ summed over, no details
- also have interactions between "spectator" partons
  their effects cancel in inclusive cross sections thanks to unitarity
  but they affect the final state X

Multiparton interactions



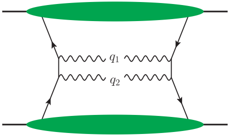
- secondary, tertiary etc. interactions generically take place in hadron-hadron collisions
- predominantly low-p_T scattering $\rightsquigarrow$ underlying event
- at high collision energy can be hard $\rightsquigarrow$ multiple hard scattering
- many studies

  theory: phenomenology, theory foundations (1980s, recent activity)
  experiment: ISR, SPS, HERA (photoproduction), Tevatron, LHC
  Monte Carlo generators: Pythia, Herwig++, Sherpa, . . .

  and ongoing activity: see e.g. the MPI@LHC workshop series
  http://indico.cern.ch/event/305160
- here: concentrate on double hard scattering (DPS)

Single vs. double hard scattering

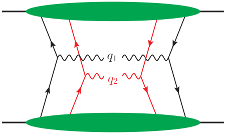
- example: prod'n of two gauge bosons, transverse momenta $\boldsymbol{q}_{T1}$ and $\boldsymbol{q}_{T2}$



single scattering:

$|\boldsymbol{q}_{T1}|$ and $|\boldsymbol{q}_{T1}| \sim$ hard scale Q^2

$|\boldsymbol{q}_{T1} + \boldsymbol{q}_{T2}| \ll Q^2$



double scattering:

both $|\boldsymbol{q}_{T1}|$ and $|\boldsymbol{q}_{T1}| \ll Q^2$

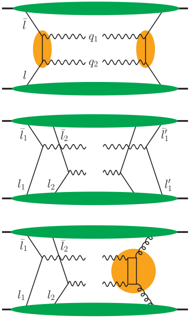
- for transv. mom. $\sim \Lambda \ll Q$:

$$\frac{d\sigma_{\text{single}}}{d^2\boldsymbol{q}_{T1}\, d^2\boldsymbol{q}_{T2}} \sim \frac{d\sigma_{\text{double}}}{d^2\boldsymbol{q}_{T1}\, d^2\boldsymbol{q}_{T2}} \sim \frac{1}{Q^4\,\Lambda^2}$$

but single scattering populates larger phase space :

$$\sigma_{\text{single}} \sim \frac{1}{Q^2} \gg \sigma_{\text{double}} \sim \frac{\Lambda^2}{Q^4}$$

Scale and energy dependence

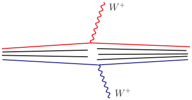


$\frac{s\,d\sigma}{\prod_{i=1}^{2} dx_i\, d\bar{x}_i\, d^2\boldsymbol{q}_i}$	$\frac{s\,d\sigma}{\prod_{i=1}^{2} dx_i\, d\bar{x}_i}$
$\frac{1}{\Lambda^2 Q^2}$	1
$\frac{1}{\Lambda^2 Q^2}$	$\frac{\Lambda^2}{Q^2}$
$\frac{1}{\Lambda^2 Q^2}$	$\frac{\Lambda^2}{Q^2}$

- interference between single and double scattering:
  - leading power when differential in $\boldsymbol{q}_i$
  - power suppressed when $\int d^2\boldsymbol{q}_i$, twist-three parton distributions
- at small $x_1 \sim x_2 \sim x$ expect
  - single scattering $\propto x^{-\lambda}$ with $xf(x) \sim x^{-\lambda}$
  - double scattering $\propto x^{-2\lambda}$
  - interference ? how do three-particle correlators behave for small x ?

A numerical estimate

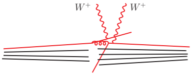
gauge boson pair production

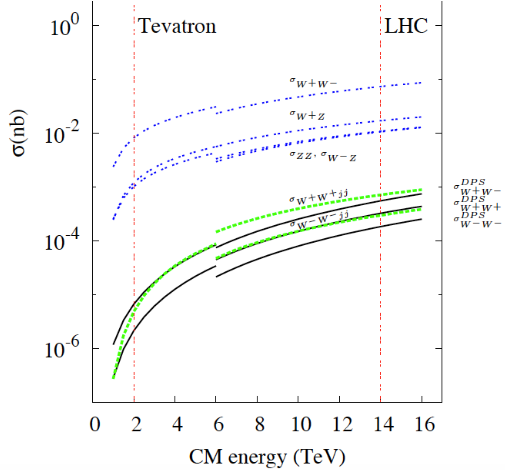


single scattering:

$qq \to qq + W^+W^+$

suppressed by α_s^2

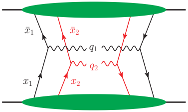




J Gaunt et al, arXiv:1003.3953

based on pocket formula to be discussed shortly

Cross section formula

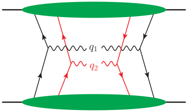


$$\frac{d\sigma_{\text{double}}}{dx_1\, d\bar{x}_1\; dx_2\, d\bar{x}_2} = \frac{1}{C}\, \hat{\sigma}_1\, \hat{\sigma}_2 \int d^2\boldsymbol{y}\; F(x_1, x_2, \boldsymbol{y})\, F(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

$$\begin{aligned} C &= \text{combinatorial factor} \\ \hat{\sigma}_i &= \text{parton-level cross sections} \\ F(x_1, x_2, \boldsymbol{y}) &= \text{double parton distribution (DPD)} \\ \boldsymbol{y} &= \text{transv. distance between partons} \end{aligned}$$

- follows from Feynman graphs and hard-scattering approximation
  no semi-classical approximation required
- can make $\hat{\sigma}_i$ differential in further variables (e.g. for jet pairs)
- can extend $\hat{\sigma}_i$ to higher orders in α_s
  get usual convolution integrals over x_i in $\hat{\sigma}_i$ and F

Cross section formula



- for measured transv. momenta

$$\frac{d\sigma_{\text{double}}}{dx_1\, d\bar{x}_1\, d^2\boldsymbol{q}_1\;\, dx_2\, d\bar{x}_2\, d^2\boldsymbol{q}_2} = \frac{1}{C}\, \hat{\sigma}_1\, \hat{\sigma}_2$$

$$\times \left[\prod_{i=1}^{2} \int d^2\boldsymbol{k}_i\, d^2\bar{\boldsymbol{k}}_i\, \delta(\boldsymbol{q}_i - \boldsymbol{k}_i - \bar{\boldsymbol{k}}_i) \right] \int d^2\boldsymbol{y}\, F(x_i, \boldsymbol{k}_i, \boldsymbol{y})\, F(\bar{x}_i, \bar{\boldsymbol{k}}_i, \boldsymbol{y})$$

- $F(x_i, \boldsymbol{k}_i, \boldsymbol{y}) = k_T$ dependent two-parton distribution
- has structure of a Wigner function:
  $\boldsymbol{k}_1, \boldsymbol{k}_2 =$ transv. parton momenta averaged over $\mathcal{A}$ and $\mathcal{A}^*$
  $\boldsymbol{y} =$ transv. distance between partons averaged over $\mathcal{A}$ and $\mathcal{A}^*$

Pocket formula

- make simplest possible assumptions
- if two-parton density factorizes as

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

  where $f(x_i) =$ usual PDF
- if assume same $G(\boldsymbol{y})$ for all parton types
  then cross sect. formula turns into

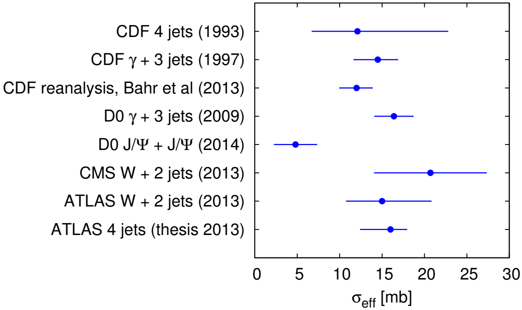
$$\frac{d\sigma_{\text{double}}}{dx_1\, d\bar{x}_1\;\, dx_2\, d\bar{x}_2} = \frac{1}{C}\, \frac{d\sigma_1}{dx_1\, d\bar{x}_1}\; \frac{d\sigma_2}{dx_2\, d\bar{x}_2}\; \frac{1}{\sigma_{\text{eff}}}$$

  with $1/\sigma_{\text{eff}} = \int d^2\boldsymbol{y}\; G(\boldsymbol{y})^2$

  $\rightsquigarrow$ scatters are completely independent
- underlies bulk of phenomenological estimates
- fails if any of the above assumptions is invalid
  or if original cross sect. formula misses important contributions
  (examples later)

  cf. Calucci, Treleani 1999; Frankfurt, Strikman, Weiss 2003-04; Blok et al 2013

Experimental investigations (very incomplete)



- other channels:
  - double charm production ($c\bar{c}c\bar{c}$) LHCb 2011, 2012; CMS 2014
    $J/\Psi + J/\Psi$, $J/\Psi + C$, $C + C$ with $C = D^0, D^+, D_s^+, \Lambda_c^+$
  - $W + J/\Psi$ ATLAS 2014

Parton correlations

- if neglect correlations between two partons

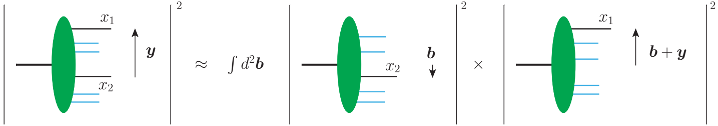
$$F(x_1, x_2, \boldsymbol{y}) = \int d^2\boldsymbol{b}\ f(x_1, \boldsymbol{b}+\boldsymbol{y})\, f(x_2, \boldsymbol{b})$$

where $f(x_i, \boldsymbol{y})$ = impact parameter dependent single-parton density

and if neglect correlations between x and $\boldsymbol{y}$ of single parton

$$f(x_i, \boldsymbol{y}) = f(x_i) F(\boldsymbol{y})$$

then in pocket formula $G(\boldsymbol{y}) = \int d^2\boldsymbol{b}\ F(\boldsymbol{b})\, F(\boldsymbol{b}+\boldsymbol{y})$



- for Gaussian $F(\boldsymbol{b})$ with average $\langle \boldsymbol{b}^2 \rangle$

$$\sigma_{\text{eff}} = 4\pi \langle \boldsymbol{b}^2 \rangle = 41\,\text{mb}\ \times \langle \boldsymbol{b}^2 \rangle / (0.57\,\text{fm})^2$$

determinations of $\langle \boldsymbol{b}^2 \rangle$ from form factors or GPDs: $(0.57\,\text{fm} - 0.67\,\text{fm})^2$

if $F(\boldsymbol{b})$ is Fourier trf. of dipole then $41\,\text{mb} \to 36\,\text{mb}$

is $\gg$ $\sigma_{\text{eff}} \sim 5$ to $20\,\text{mb}$ from experimental extractions

Parton correlations

at certain level of accuracy expect correlations between

- x_1 and x_2 of partons
  - most obvious: energy conservation $\Rightarrow\ x_1 + x_2 \le 1$
  - significant x_1 – x_2 correlations found in constituent quark model

    Rinaldi, Scopetta, Vento 2013

- x_i and $\boldsymbol{y}$

  even for single partons see correlations between x and $\boldsymbol{b}$ distribution
  - HERA results on $\gamma p \to J/\Psi\, p$ give

    $\langle \boldsymbol{b}^2 \rangle \propto \text{const} + 4\alpha' \log(1/x)$ with $4\alpha' \approx (0.16\,\text{fm})^2$

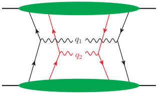
    for gluons with $x \sim 10^{-3}$
  - lattice calculations of x^0, x^1, x^2 moments

    $\to$ strong decrease of $\langle \boldsymbol{b}^2 \rangle$ with x above ~ 0.1

plausible to expect similar correlations in double parton distributions
even if two partons not uncorrelated

impact on observables: L Frankfurt, M Strikman, C Weiss 2003
R Corke, T Sjöstrand 2011; B Blok, P Gunnellini 2015

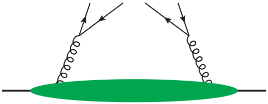
Spin correlations



- polarizations of two partons can be correlated even in unpolarized proton
  - quarks: longitudinal and transverse pol.
  - gluons: longitudinal and linear pol.
- can be included in factorization formula
  $\rightsquigarrow$ extra terms with polarized DPDs and partonic cross sections
- if spin correlations are large $\to$ large effects for
  rate and final state distributions of double hard scattering
  A. Manohar, W. Waalewijn 2011; T. Kasemets, MD 2012
  M. Echevarria, T. Kasemets, P. Mulders, C. Pisano 2015
- large spin correlations found in MIT bag model
  Chang, Manohar, Waalewijn 2012
- for x_1, x_2 small: size of correlations unknown
  known: evolution to higher scales tends to wash out polarization
  unpol. densities evolve faster than polarized ones
  MD, T. Kasemets 2014

Behavior at small interparton distance

- for $\boldsymbol{y} \ll 1/\Lambda$ in perturbative region $F(x_1, x_2, \boldsymbol{y})$ dominated by graphs with splitting of single parton



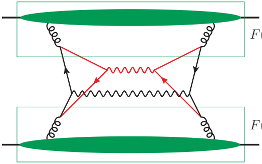
- gives strong correlations in x_1, x_2, spin and color between two partons

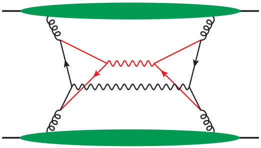
  e.g. -100% correlation for longitudinal pol. of q and $\bar{q}$

- can compute short-distance behavior:

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

Problems with the splitting graphs

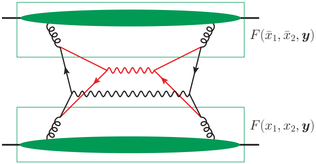


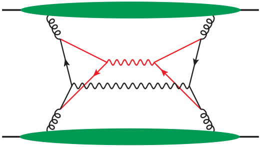


- contribution from splitting graphs in cross section gives UV divergent integrals $\int d^2\boldsymbol{y}\, F(x_1, x_2, \boldsymbol{y})\, F(\bar{x}_1, \bar{x}_2, \boldsymbol{y}) \sim \int d\boldsymbol{y}^2/\boldsymbol{y}^4$
- double counting problem between double scattering with splitting and single scattering at loop level

  MD, Ostermeier, Schäfer 2011; Gaunt, Stirling 2011; Gaunt 2012
  Blok, Dokshitzer, Frankfurt, Strikman 2011; Ryskin, Snigirev 2011, 2012
  already noted by Cacciari, Salam, Sapeta 2009
- possible solution:
  only large $\boldsymbol{y}$ in double, only small $\boldsymbol{y}$ in single hard scattering
  remains to be worked out

Problems with the splitting graphs





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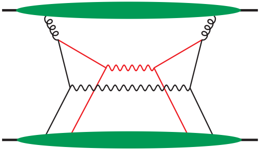
- also have graphs with single PDF for one and double PDF for other proton

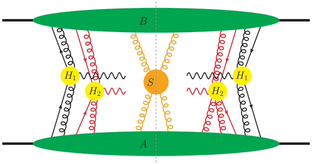
$\sim \int d\boldsymbol{y}^2/\boldsymbol{y}^2 \;\times F_{\textit{no split}}(x_1, x_2, \boldsymbol{y})$

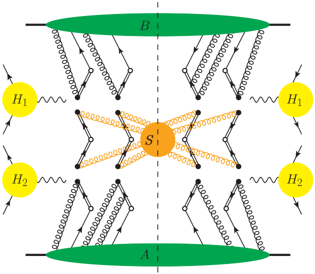
B Blok et al 2011-13
J Gaunt 2012
B Blok, P Gunnellini 2015



Does the DPS cross section factorize at all?

- problem already for single hard scattering: exchange of soft gluons

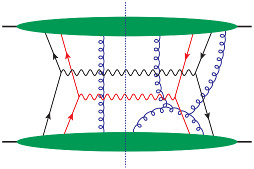




- gluons with "generic" soft momentum: to 1st approx. only see colour charge of fast partons
  ⇝ approx. fast partons by Wilson lines
  ⇝ soft gluon exchange factorises
  ⇝ can compute effects of Sudakov logarithms, Sivers effect, etc
- approx. fails if transverse ≫ longitudinal gluon mom. (Glauber region)

Glauber gluons

- physics of Glauber gluon exchange:
  low-angle scattering of partons moving in opposite directions
- physical effects:
  deflection of beam remnants,
  specific spin asymmetries
  T Rogers 2013; J Gaunt 2014; M Zeng 2015



- in initial state: avoid Glauber by deforming gluon mom. in complex plane
- in final state: cancel in sum over all final state cuts
  if observable sufficiently inclusive
- proof of soft-gluon-cancellation for single Drell-Yan process:
  G Bodwin 1984; J Collins, G Sterman, D Soper 1988; J Collins 2011
  - works for collinear and TMD factorisation
  - only with fast partons moving one of two directions
  - for more directions (e.g. jet production) should work in collin. fact.
    unsolved problems with TMDs T Rogers, P Mulders 2010
- can generalise from single to double Drell-Yan process
  MD, J. Gaunt, D. Ostermeier, D. Plößl, A. Schäfer: in preparation

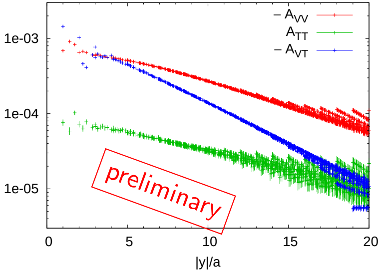
Conclusions

- multiparton interactions ubiquitous in hadron-hadron collisions
  multiple hard scattering often suppressed, but not necessarily
  - in specific kinematics
  - for multi-differential cross sections, high-multiplicity final states
- most phenomenology relies on strong simplifications
  some improvements are being explored
- have more and more elements for a formulation of factorization
  but important open questions remain
  - crosstalk with single hard scattering at small distances
- double hard scattering depends on detailed hadron structure
  - transverse spatial distribution
  - different correlation and interference effects
- subject remains of high interest for
  - control over final states at LHC
  - understanding QCD dynamics

Backup

Spin correlations

- can (almost) compute x_1, x_2 moments of DPDs in lattice QCD
- pilot study for the pion G Bali, L Castagnini, S Collins, MD, M Engelhardt, J Gaunt, B Gläßle, A Sternbeck, A Schäfer, Ch Zimmermann

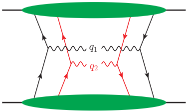


lattice spacing $a \approx 0.07\,\mathrm{fm}$

pion mass $280\,\mathrm{MeV}$

- VV: spin averaged
- TT: transverse spin corr. $\propto\ \boldsymbol{s}_u \cdot \boldsymbol{s}_{\bar{d}}$
  find very small $A_{TT} \sim -0.1 \times A_{VV}$
- AA: longitudinal spin corr. even smaller (not shown)
- VT: correlation $\propto\ \boldsymbol{y} \cdot \boldsymbol{s}_{\bar{d}}$
  maximal at small $|\boldsymbol{y}|$, then decreases

Color correlations

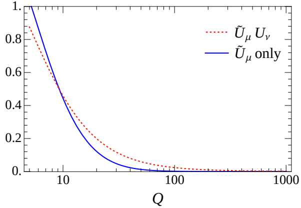


- color of two quarks and gluons can be correlated
- suppressed by Sudakov logarithms

Mekhfi 1988

. . . but not necessarily negligible
for moderately hard scales

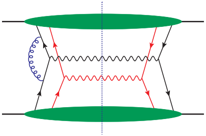
Manohar, Waalewijn arXiv:1202:3794

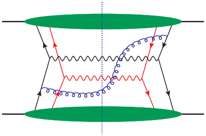


U = Sudakov factor for quarks

Q = hard scale

from incomplete cancellation between graphs with real/virtual soft gluons





Scale evolution for distributions without color correlation

- if define two-parton distributions as operator matrix elements in analogy with usual PDFs

$$F(x_1, x_2, \boldsymbol{y}; \mu) \sim \langle p | \mathcal{O}_1(\boldsymbol{0}; \mu)\, \mathcal{O}_2(\boldsymbol{y}; \mu) | p \rangle \qquad f(x;\mu) \sim \langle p | \mathcal{O}(\boldsymbol{0}; \mu) | p \rangle$$

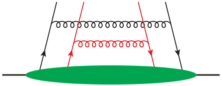
  where $\mathcal{O}(\boldsymbol{y}; \mu)$ = twist-two operator renormalized at scale μ

- $F(x_i, \boldsymbol{y})$ for $\boldsymbol{y} \neq \boldsymbol{0}$:

  separate DGLAP evolution for partons 1 and 2

$$\frac{d}{d \log \mu} F(x_i, \boldsymbol{y}) = P \otimes_{x_1} F + P \otimes_{x_2} F$$

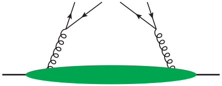
  two independent parton cascades



- $\int d^2\boldsymbol{y}\, F(x_i, \boldsymbol{y})$:

  extra term from $2 \to 4$ parton transition
  since $F(x_i, \boldsymbol{y}) \sim 1/\boldsymbol{y}^2$

  Kirschner 1979; Shelest, Snigirev, Zinovev 1982
  Gaunt, Stirling 2009; Ceccopieri 2011



Scale evolution for distributions without color correlation

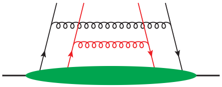
- if define two-parton distributions as operator matrix elements in analogy with usual PDFs

$$F(x_1, x_2, \boldsymbol{y}; \mu) \sim \langle p | \mathcal{O}_1(\boldsymbol{0}; \mu)\, \mathcal{O}_2(\boldsymbol{y}; \mu) | p \rangle \qquad f(x; \mu) \sim \langle p | \mathcal{O}(\boldsymbol{0}; \mu) | p \rangle$$

where $\mathcal{O}(\boldsymbol{y}; \mu)$ = twist-two operator renormalized at scale μ

- $F(x_i, \boldsymbol{y})$ for $\boldsymbol{y} \neq \boldsymbol{0}$:

separate DGLAP evolution for partons 1 and 2

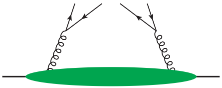


$$\frac{d}{d \log \mu} F(x_i, \boldsymbol{y}) = P \otimes_{x_1} F + P \otimes_{x_2} F$$

two independent parton cascades

- $\int d^2\boldsymbol{y}\, F(x_i, \boldsymbol{y})$:

extra term from $2 \to 4$ parton transition since $F(x_i, \boldsymbol{y}) \sim 1/\boldsymbol{y}^2$



Kirschner 1979; Shelest, Snigirev, Zinovev 1982
Gaunt, Stirling 2009; Ceccopieri 2011

Phenomenological estimates of double parton scattering

- pocket formula used in most estimate for DPS contribution
- some recent studies (apologies for omissions):
  - double dijets — Domdey, Pirner, Wiedemann 2009; Berger, Jackson, Shaughnessy 2009
  - W/Z + jets — Maina 2009, 2011
  - $\gamma\gamma$ + jets — Tao et al, 2015
  - like-sign W pairs — Kulesza, Stirling 2009; Gaunt et al 2010; Berger et al 2011
  - double Drell-Yan — Kom, Kulesza, Stirling 2011
  - double charmonium — Kom, Kulesza, Stirling 2011; Baranov et al. 2011, 2012; Novoselov 2011
  - double charm — Berezhnoy et al 2012; Luszczak et al 2011; Cazaroto et al 2013; Maciula, Szczurek 2012, 2013; van Hameren, Maciula, Szczurek 2014, 2015
- also several studies for proton-nucleus collisions