Conventional versus single ladder splitting contributions to double gluon-gluon initiated processes.

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Based on **Phys. Rev. D 90 (2014) 054017** with **Rafal Maciula** & **Antoni Szczurek**

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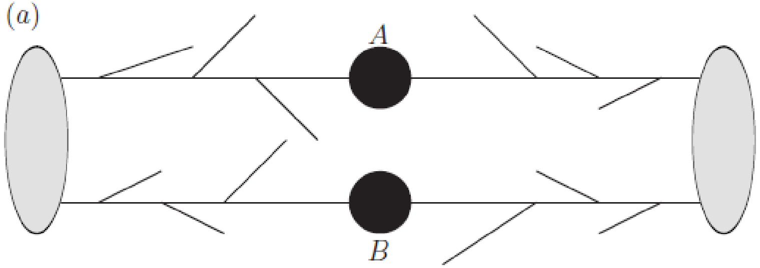
2v2 and 2v1 mechanisms in DPS

Two types of diagram known to contribute to double parton scattering total cross section at leading logarithmic order:

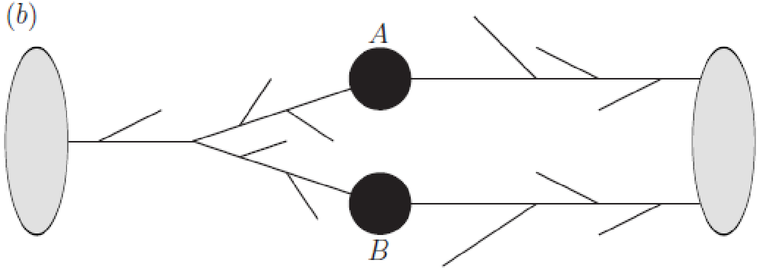
Blok et al., Eur.Phys.J. C72 (2012) 1963
JG, JHEP 1301 (2013) 042

(a)



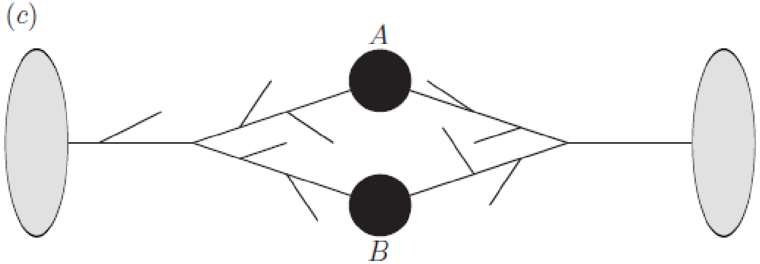
'Conventional' DPS mechanism (2v2 process)

(b)



'Ladder splitting' DPS mechanism (2v1 process)

(c)



Contribution from double splitting / 1v1 mechanism?
Overlap between this and SPS contribution → often taken to be pure SPS.

JG and Stirling, JHEP 1106 048 (2011) & arXiv:1202.3056
Manohar, Waalewijn Phys.Lett. 713 (2012) 196–201.
Blok et al., Eur.Phys.J. C72 (2012) 1963

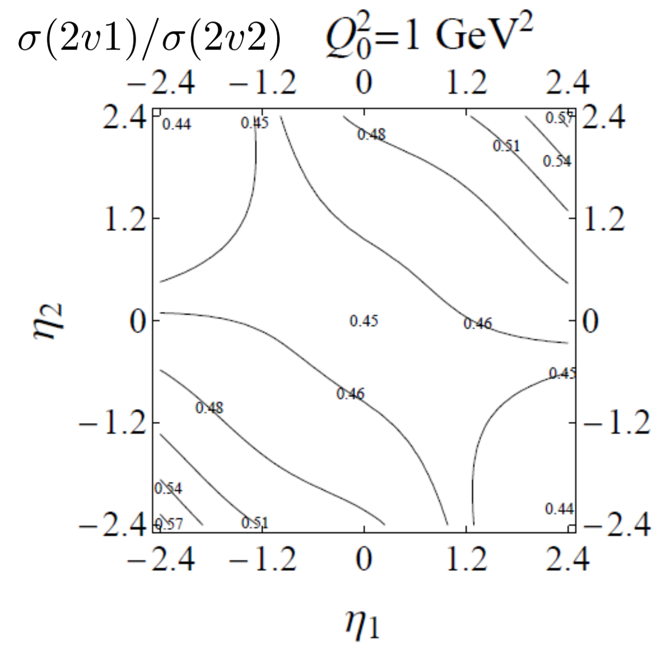
Our purpose is to compare relative sizes of 2v2 & 2v1 – will ignore 1v1.

Numerical size of 2v1 contribution

One existing study of numerical size of 2v1 contribution – Blok, Dokshitzer, Frankfurt, Strikman (BDFS) Eur.Phys.J. C74 (2014) 2926

They studied size of 2v1 effects in four jet, γ+3j, W^+jj and W^+W^- production.

They found a sizable contribution from 2v1 DPS graphs compared to 2v2 DPS graphs in these processes.

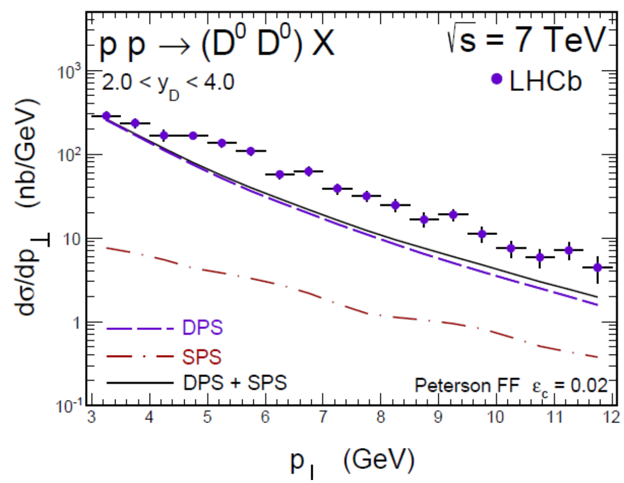


$W jj, p_T(j) \simeq 30\text{GeV}$

$$\sigma(2v1)/\sigma(2v2) \sim 1/2 - 1$$

Aim

Our goal: Study size of 2v1 effects in DPS processes where hard subprocesses predominantly involve gg fusion – 2 x S-wave (η) or P-wave (χ) quarkonia, 2 x Higgs bosons, or double open charm ($c\bar{c}c\bar{c}$).

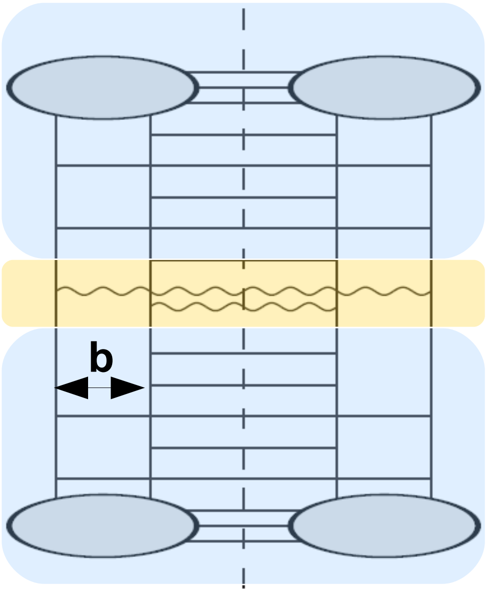


One motivation: previous study of DPS charm production by van Hameren, Maciula and Szczurek – some signal missing. 2v1?

Phys. Rev. D89 (2014) 094019

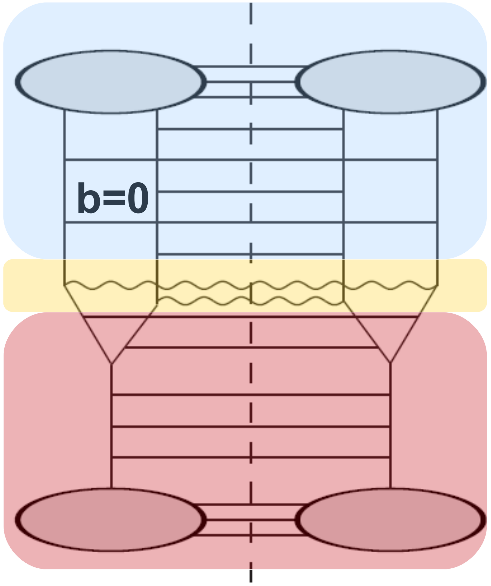
Sketch of the formalism

$$\sigma^{D}_{(A,B)}(s) = \sigma^{D,2v2}_{(A,B)}(s) + \sigma^{D,1v2}_{(A,B)}(s)$$



$$\sigma^{D,2v2}_{(A,B)}(s) = \frac{m}{2}\int dx_1 dx_2 dy_1 dy_2 \hat{\sigma}_{ik\to A}(\hat{s} = x_1 y_1 s)\hat{\sigma}_{jl\to B}(\hat{s} = x_2 y_2 s)$$
$$\times \int d^2 b \Gamma^{ij}_{p,indep}(x_1, x_2, b; Q^2)\Gamma^{kl}_{p,indep}(y_1, y_2, b; Q^2)$$

Independent pair 2pGPD



$\int d^2\mathbf{b}$

$$\sigma^{D,1v2}_{(A,B)}(s) = 2 \times \frac{m}{2}\int dx_1 dx_2 dy_1 dy_2 \hat{\sigma}_{ik\to A}(\hat{s} = x_1 y_1 s)\hat{\sigma}_{jl\to B}(\hat{s} = x_2 y_2 s)$$
$$\times \hat{D}^{ij}_p(x_1, x_2; Q^2)\Gamma^{kl}_{p,indep}(y_1, y_2, \mathbf{b} = \mathbf{0}; Q^2)$$

Ladder splitting double PDF (dPDF)

Sketch of the formalism

Assuming: $\Gamma^{ij}(x_1, x_2, \mu_1^2, \mu_2^2, b) = D^{ij}(x_1, x_2, \mu_1^2, \mu_2^2)F(b)$,

Independent pair dPDF

$$\sigma(2v2) = \frac{m}{2}\frac{1}{\sigma_{eff,2v2}}\int dx_1 dx_2 dx'_1 dx'_2 \; \sigma_{gg\to\chi}(x_1 x'_1 s) \; \sigma_{gg\to\chi}(x_2 x'_2 s) \times D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2) D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2)$$

$$\sigma(2v1) = \frac{m}{2}\frac{1}{\sigma_{eff,2v1}}\int dx_1 dx_2 dx'_1 dx'_2 \; \sigma_{gg\to\chi}(x_1 x'_1 s) \; \sigma_{gg\to\chi}(x_2 x'_2 s) \times \left(\hat{D}^{gg}(x'_1, x'_2, \mu_1^2, \mu_2^2) D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2) + (x_i \leftrightarrow x'_i)\right) ,$$

with $\quad \frac{1}{\sigma_{eff,2v2}} = \int d^2b[F(b)]^2 , \quad \frac{1}{\sigma_{eff,2v1}} = F(b=0)$.

Sketch of the formalism

If independent branching partons are uncorrelated in transverse space:

$$F(b) = \int d^2r \rho(r)\rho(b-r)$$

Parton density in transverse plane

Various one-parameter forms for ρ:

Transverse density profile	$\rho(r)$	$\sigma_{eff,1v2}/\sigma_{eff,2v2}$
Hard Sphere	$\rho(r) = \frac{3}{2\pi R^2}(1-r^2/R^2)^{1/2}\Theta(R-r)$	0.52
Gaussian	$\rho(r) = \frac{1}{2\pi R^2}\exp\left(-\frac{r^2}{2R^2}\right)$	0.50
Top Hat	$\rho(r) = \frac{1}{\pi R^2}\Theta(R-r)$	0.46
Dipole	$\rho(r) = \int \frac{d^2\Delta}{(2\pi)^2} e^{i\mathbf{\Delta}\cdot\mathbf{r}}(\Delta^2/m_g^2+1)^{-2}$	0.43
Exponential	$\rho(r) = \int dz \frac{1}{8\pi R^3}\exp(-\sqrt{r^2+z^2}/R)$	0.43

All ~ 0.5

We take $\sigma_{eff,1v2}$ / $\sigma_{eff,2v2}$ = 0.5.

Where necessary we take $\sigma_{eff,2v2}$ = 30fb. This is a plausible figure – e.g. GPD data implies a ρ function that yields a $\sigma_{eff,2v2}$ in this ballpark.

Frankfurt, Strikman, Weiss, Phys. Rev. D 69 (2004) 114010

Here we ignore spin, colour, flavour interference effects.Colour and flavour interference likely small, & spin effects will be discussed in talk by Tomas Kasemets.

Numerical implementation of dPDFs

Ladder splitting dPDFs (equal scale):

$$\hat{D}^{j_1 j_2}(x_1, x_2; \mu^2 = Q_0^2) = 0$$

Set to zero at some low scale:

Q_0 = 'scale at which perturbative splittings begin' (we take Q_0 = 1 GeV)

Evolve up using a numerical implementation of double DGLAP equation:

$$\mu^2 \frac{d\hat{D}^{j_1 j_2}(x_1, x_2; \mu^2)}{d\mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \Bigg[\underbrace{\sum_{j_1'} \int_{x_1}^{1-x_2} \frac{dx_1'}{x_1'} \hat{D}^{j_1' j_2}(x_1', x_2; \mu^2) P_{j_1' \to j_1}\left(\frac{x_1}{x_1'}\right) + \sum_{j_2'} \int_{x_2}^{1-x_1} \frac{dx_2'}{x_2'} \hat{D}^{j_1 j_2'}(x_1, x_2'; \mu^2) P_{j_2' \to j_2}\left(\frac{x_2}{x_2'}\right)}_{\text{Emission from double ladder following splitting}}$$

$$+ \underbrace{\sum_{j'} D^{j'}(x_1 + x_2; \mu^2) \frac{1}{x_1 + x_2} P_{j' \to j_1 j_2}\left(\frac{x_1}{x_1 + x_2}\right)}_{\text{Ladder splitting}} \Bigg].$$

Shelest, Snigirev, Zinovev, Phys. Lett. B113 (1982) 325., Theor. Math. Phys. 51 (1982) 523–528

We use MSTW2008LO PDFs for single PDF in this equation.

Numerical implementation of dPDFs

For unequal scales, start with equal scale dPDFs and add extra DGLAP emission to higher scale leg – e.g. for $\mu_1 > \mu_2$ the evolution equation is:

$$\mu_1^2 \frac{d\hat{D}^{j_1 j_2}(x_1, x_2; \mu_1^2, \mu_2^2)}{d\mu_1^2} = \frac{\alpha_s(\mu_1^2)}{2\pi} \left[\sum_{j_1'} \int_{x_1}^{1-x_2} \frac{dx_1'}{x_1'} \hat{D}^{j_1' j_2}(x_1', x_2; \mu_1^2, \mu_2^2) P_{j_1' \to j_1}\left(\frac{x_1}{x_1'}\right) \right]$$

Independent pair dPDFs: $D^{ij}(x_1, x_2, \mu_1^2, \mu_2^2) \simeq D^i(x_1, \mu_1^2) D^j(x_2, \mu_2^2) \theta(1 - x_1 - x_2)$

MSTW2008LO PDFs

Could do a better job by using 'proper' evolution equation (independent double DGLAP but with effects of phase space constraint $x_1 + x_2 < 1$), but numerically very little difference for x_1, $x_2 \ll 1$. Diehl, Keane, Kasemets, JHEP 1405 (2014) 118

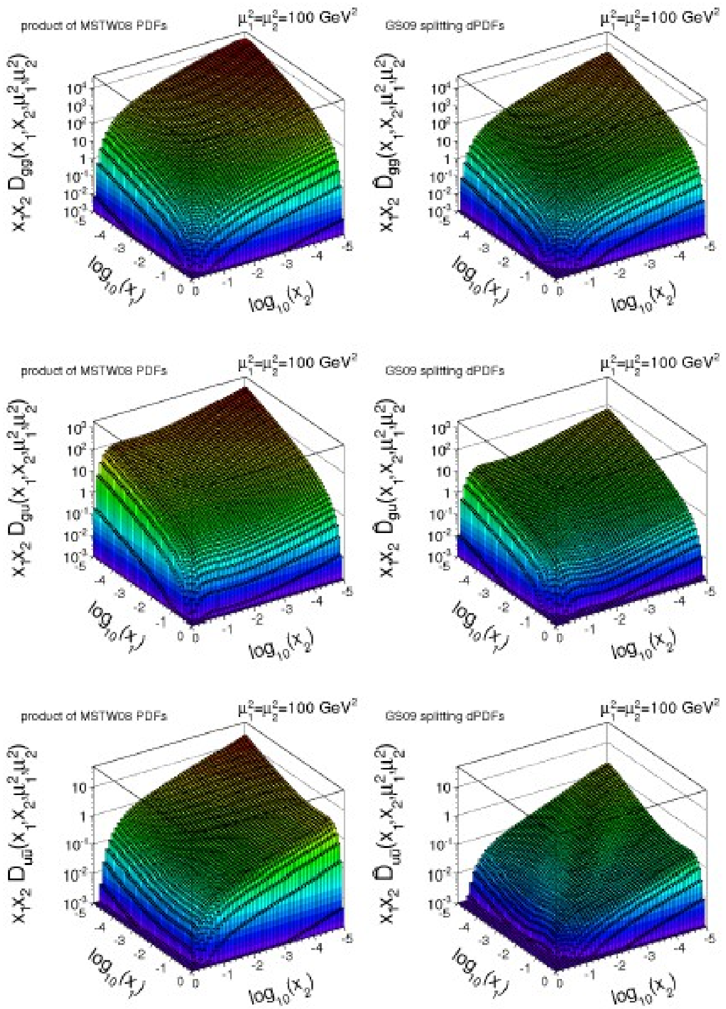
Results - dPDFs

Independent pair Ladder splitting

gg

gu

$u\bar{u}$



First: let's look at the results on the level of the dPDFs

We plot dPDFs at $\mu_1 = \mu_2 = 10$ GeV for a few representative parton combinations

Shapes different for different parton combinations, but rather similar between independent pair and ladder splitting.

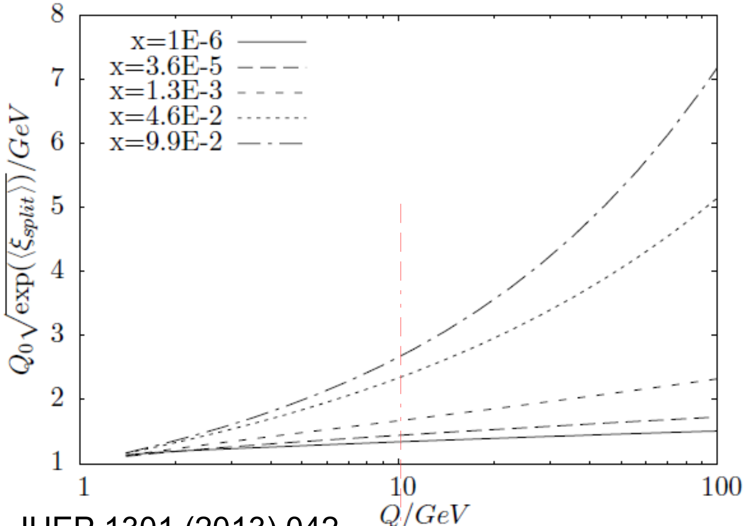
For low x splitting dPDF ~ independent pair dPDF / 10

Results - dPDFs

Plot ratios: very flat for small x_1, x_2!

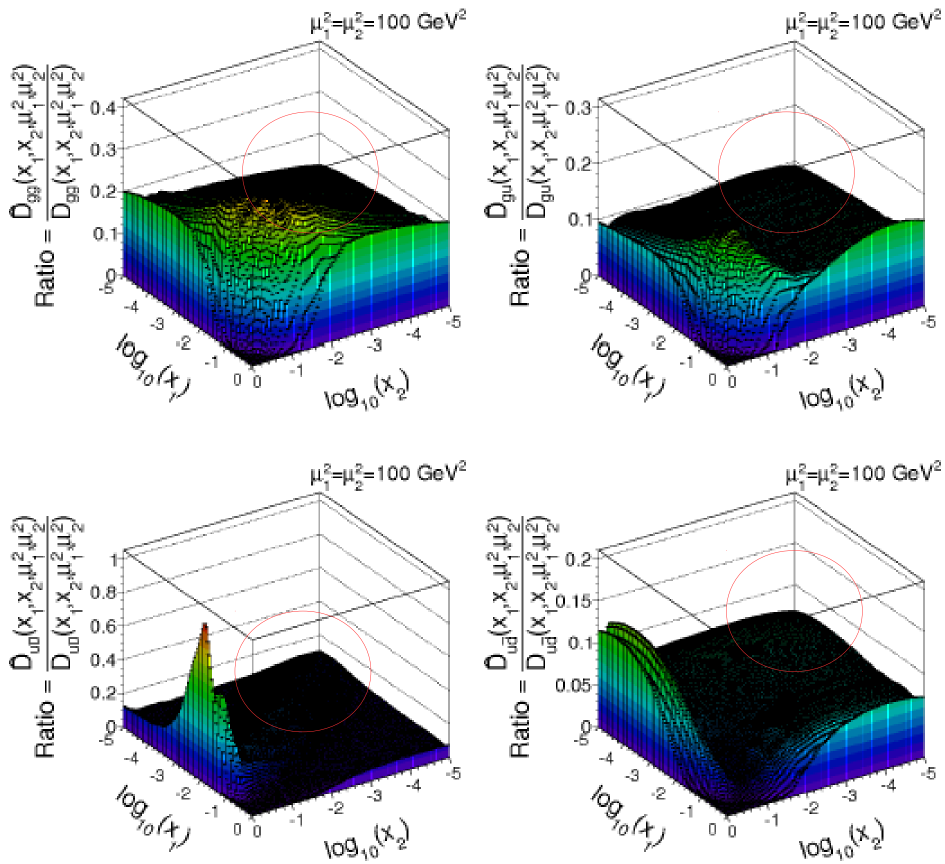
Why is this?

Explanation: for not too large x_1, x_2, the ladder splitting occurs extremely 'early' in μ:



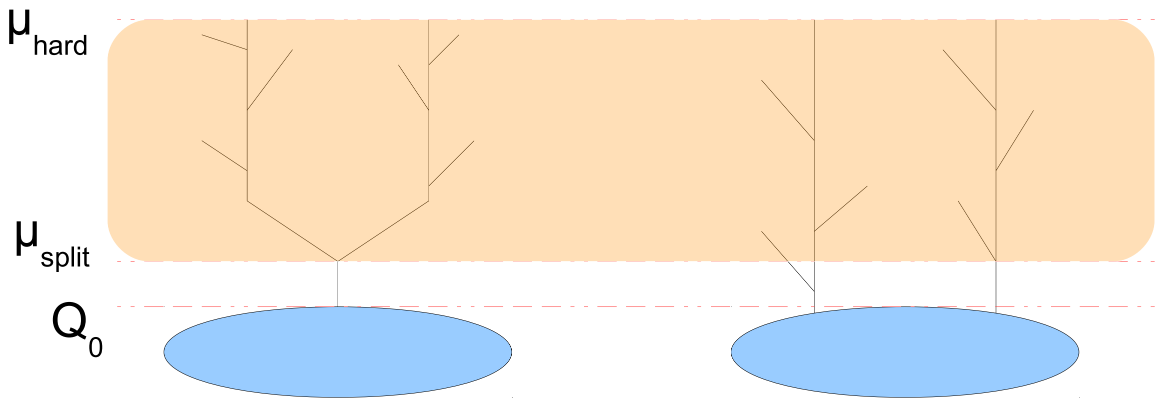
JG, JHEP 1301 (2013) 042

Splitting μ < 3 GeV



Results - dPDFs

Then over most of the evolution range, evolution of ladder splitting and independent pair dPDFs is the same.



Same evolution here – two-ladder DGLAP branching

Similar evolution causes dPDF shapes to converge.

Can test this explanation by using various toy input forms at μ = 1 GeV and then evolving them up to μ = 10 GeV using independent branching evolution. Shapes of evolved distributions were rather similar regardless of input, which supports the idea that evolution causes shapes to converge.

Quarkonia and Higgs boson production

Now look at double quarkonium (or Higgs boson) production.

Subprocess cross section (LO): $\sigma_{gg\to\chi}(\hat{s}) = C_{gg\to\chi} \cdot \delta(\hat{s} - M_{\chi}^2)$

Ratio σ(2v1)/σ(2v2) versus quarkonium mass and energy:

M (GeV) / $\sqrt{s}$ (TeV)	0.2	0.5	1.96	8.0	13.0
3.	0.840	0.775	0.667	0.507	0.437
10.	1.116	1.022	0.891	0.780	0.743
126.	–	—	1.347	1.134	1.070

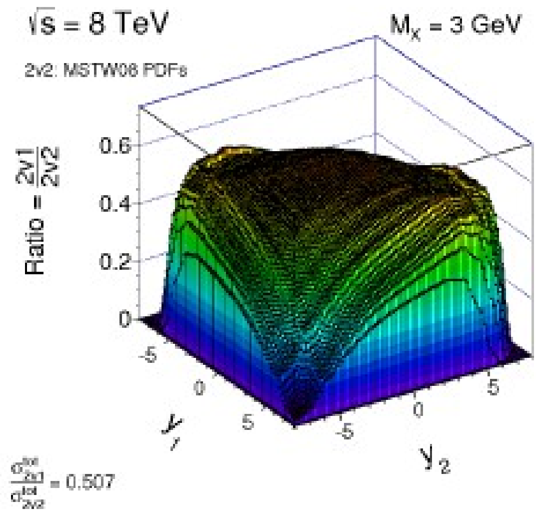
2v1 and 2v2 cross sections comparable! - as was also found by BDFS group

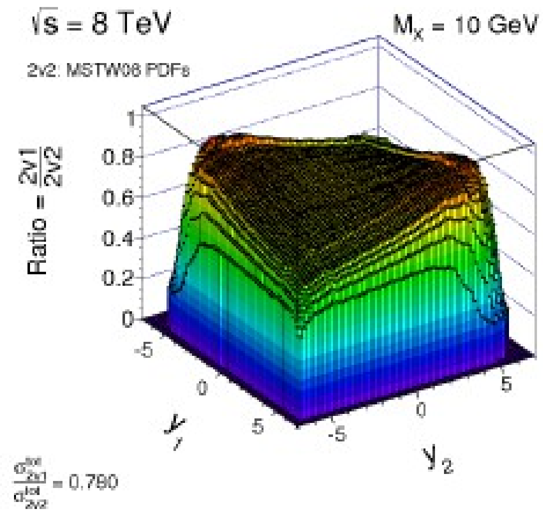
Gradual decrease of σ(2v1)/σ(2v2) with √s, as smaller x values are probed.

σ(2v1)/σ(2v2) increases as M increases, and larger x values and scales are probed.

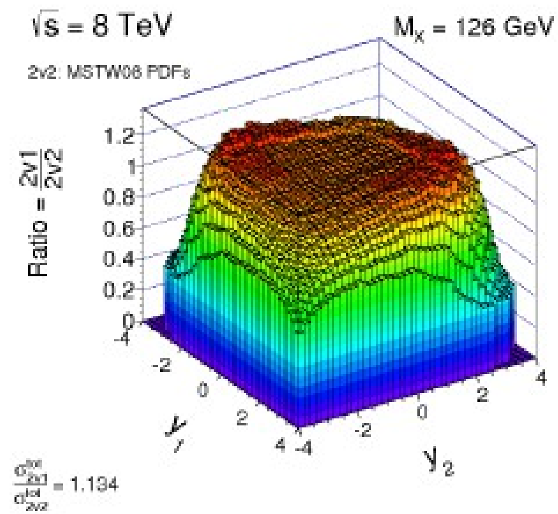
Quarkonia and Higgs boson production

Dependence of σ(2v1)/σ(2v2) on rapidities of quarkonia / Higgs bosons for fixed M and √s





Rather flat shapes – reflects similar shape of ladder splitting and independent pair dPDFs in x_1, x_2



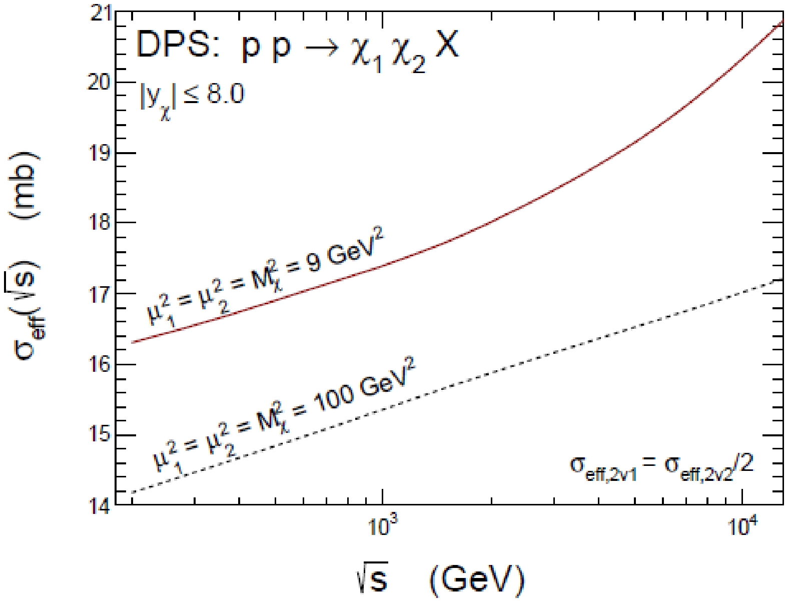
Quarkonia and Higgs boson production

Can also plot empirical σ_{eff} used by experiments: $\sigma_{eff} = \dfrac{\sigma_{A,B}(DPS)}{\sigma_A(SPS)\sigma_B(SPS)}$

If only 2v2 mechanism were present we would have $\sigma_{eff} = \sigma_{eff,2v2} = const.$

Including 2v1 mechanism:

Consequence of two components: empirical σ_{eff} increases gradually with energy, and decreases with scale



Note also that the empirical σ_{eff} value obtained is in the ball park of the values extracted in experimental measurements of DPS (~15 mb), even though we took $\sigma_{eff,2v2}$ = 30 mb.

Double open charm production – total cross sections

Now study double open charm production – can look at more differential distributions

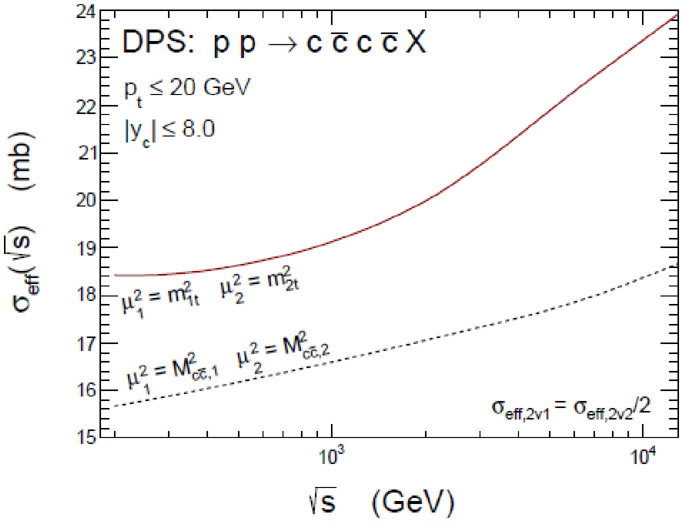
We will examine two different choices for scale of a subprocess:

- M_t^2, transverse mass of one of the charm quarks
- $M_{c\bar{c}}^2$, invariant mass of $c\bar{c}$ pair

$\sigma(2v1)/\sigma(2v2)$:

μ^2 (GeV^2) / $\sqrt{s}$ (TeV)	0.2	0.5	1.96	7.0	13.0
m_t^2	0.628	0.610	0.503	0.326	0.254
$M_{c\bar{c}}^2$	0.914	0.855	0.760	0.667	0.606

Similar ratios to quarkonium

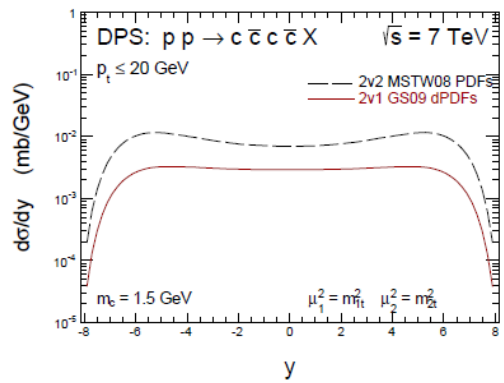


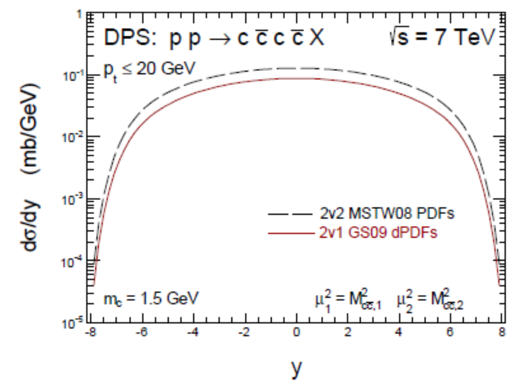
Empirical σ_{eff} - again around 15-20 mb
- large dependence on scale choice.

Double open charm production – differential cross sections

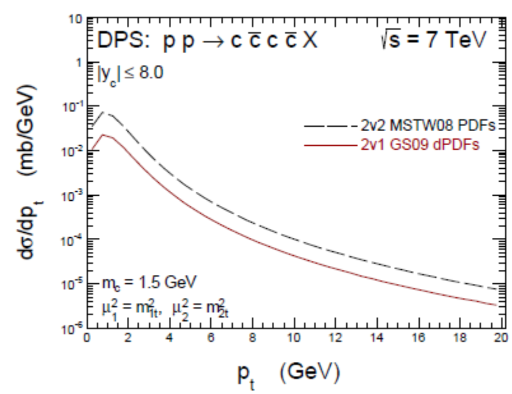
Diffential distributions:

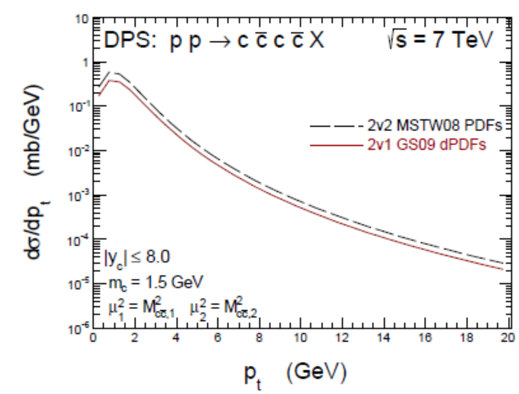
Rapidity of charm particles





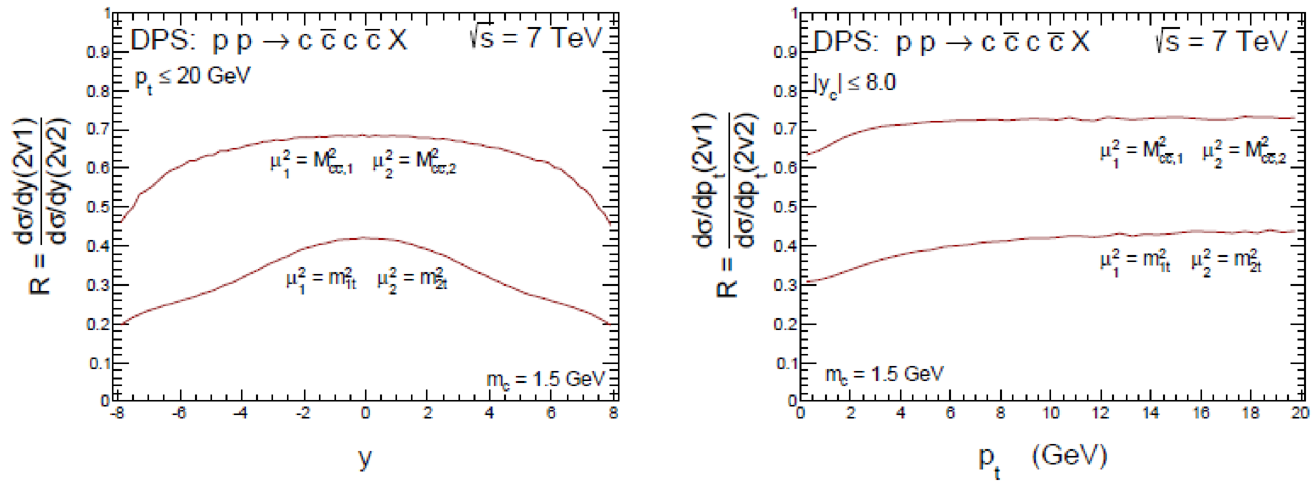
Transverse momentum of charm particles





Double open charm production – differential cross sections

2v1 contribution comparable to 2v2, but very similar in shape:



Separation of 2v1 and 2v2 very difficult!

Summary

- Discussed contribution of two DPS mechanisms, 2v2 and 2v1, to gluon-initiated processes – production of 2 x quarkonia, 2 x Higgs, and double open charm.
- Comparison on level of double PDFs – splitting dPDF very similar shape to independent pair dPDF, approximately 1/10 the size. Similar shapes result from early 1→2 splittings in splitting dPDF, resulting in similar evolution over most of range for splitting and independent ladder dPDFs.
- 2v1 mechanism can give a significant contribution to cross sections – σ(2v1)/σ(2v2) ~ 0.5 – 1 as also found by BDFS. Ratio decreases slowly with energy and increases with scale.
- In double open charm production: differential distributions very similar between conventional and parton splitting contributions – makes separation difficult!
- Presence of two components gives empirical σ_{eff} that weakly increases with energy, and weakly decreases with scale.