Double open charm production at the LHC within single- and double-parton scattering

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Outline

1. Open charm production at the LHC
   - Theoretical framework within the k_t-factorization approach
   - Inclusive single D meson spectra
   - Production of $D\overline{D}$ pairs and kinematical correlations

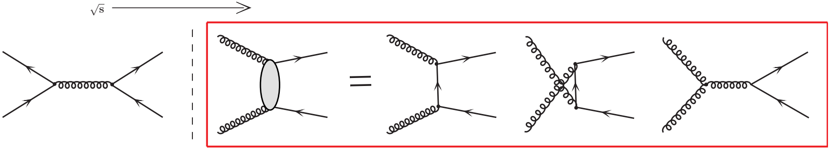
2. Mechanism of double-parton scattering (DPS)
   - Factorized theoretical model
   - Double charm (DD pairs) production vs. LHCb data

Based on:

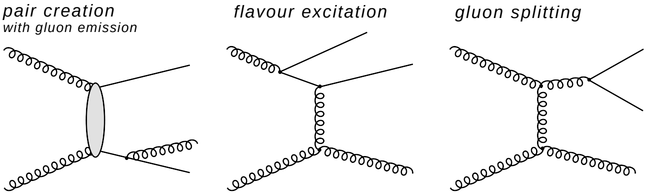
vanHameren, Maciuła, Szczurek, Phys. Rev. D89, 094019 (2014)
Maciuła, Szczurek, Phys. Rev. D87, 094022 (2013)
Maciuła, Szczurek, Phys. Rev. D87, 074039 (2013)
Łuszczak, Maciuła, Szczurek, Phys. Rev. D79, 094034 (2012)

Dominant mechanisms of heavy quarks production

- Leading order (**LO**) processes contributing to $Q\bar{Q}$ production:



- **gluon-gluon fusion** dominant at high energies
- main classes of the next-to-leading order (**NLO**) diagrams:



very important NLO corrections

- $\frac{NLO}{LO} \approx 3$ for $p_\perp \sim 0 - 3$ GeV and $y \sim 0$;
- $\frac{NLO}{LO} \gtrsim 10$ for large $p_\perp'$s or large y;

Standard approach of perturbative QCD

collinear approximation → transverse momenta of the incident partons are assumed to be zero (Wiezsacker-Williams method in QED)

- quadruply differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 p_i(x_1,\mu^2)\, x_2 p_j(x_2,\mu^2)\, \overline{|\mathcal{M}_{ij}|^2}$$

- $p_i(x_1,\mu^2)$, $p_j(x_2,\mu^2)$ - standard collinear PDFs in the proton (e.g. CTEQ, GRV, GJR, MRST, MSTW)
- NLO on-shell matrix elements well-known
  Nason et al., Nucl. Phys. B303 (1988) 607; Nucl. Phys. B327 (1989) 49
  Beenakker et al., Phys. Rev. D40 (1989) 54; Nucl. Phys. B351 (1991) 505

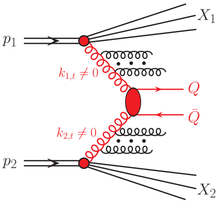
several approaches: improved schemes of NLO collinear calculations

- **FONLL** (Cacciari *et al.*) JHEP 05 (1998) 007; JHEP 03 (2001) 006
- **GM-VFNS** (Kniehl, Kramer *et al.*) Phys. Rev. D71 (2005) 014018; Phys. Rev. D79 (2009) 094009

state-of-art: σ_{tot} **and inclusive single particle spectra**

BUT cannot be applied in more exclusive studies of KINEMATICAL CORRELATIONS

Basic concepts of the k_t-factorization (semihard) approach



k_t-factorization $\longrightarrow \kappa_{1,t}, \kappa_{2,t} \neq 0$ Collins-Ellis, Nucl. Phys. B360 (1991) 3; Catani-Ciafaloni-Hautmann, Nucl. Phys. B366 (1991) 135; Ball-Ellis, JHEP 05 (2001) 053

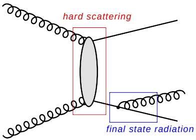
$\Rightarrow$ very efficient approach for $Q\bar{Q}$ correlations

- multi-differential cross section

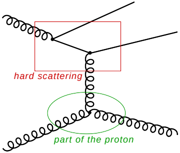
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{i^* j^* \to Q\bar{Q}}|^2}$$
$$\times \; \delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \mathcal{F}_i(x_1, \kappa_{1,t}^2)\, \mathcal{F}_j(x_2, \kappa_{2,t}^2)$$

- **LO off-shell** $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2} \Longrightarrow$ Catani-Ciafaloni-Hautmann (CCH) analytic formulae or QMRK approach with effective BFKL NLL vertices
- $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$, $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated (k_t-dependent) gluon distributions
- major part of NLO corrections effectively included

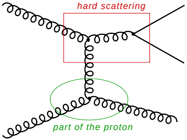
pair creation with gluon emission



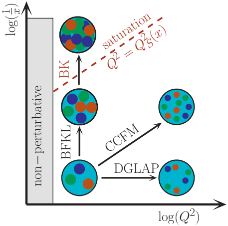
flavour excitation



gluon splitting

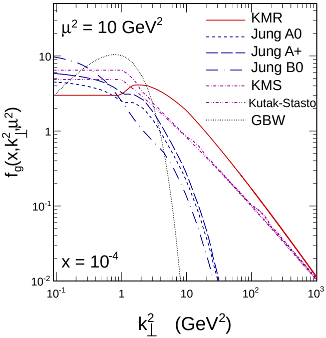


Unintegrated gluon distribution functions (UGDFs)



most popular models:

- Kwieciński, Jung (CCFM, wide range of x)
- Kimber-Martin-Ryskin (DGLAP-BFKL, wide range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, small x-values)
- Kutak-Staśto (BK, saturation, only small x-values)



already applied and tested in:

e.g. deep-inelastic structure function; inclusive charm and associated charm and jet photoproduction at HERA; dijets in photoproduction, hadroproduction and deep-inelastic scattering; electroweak boson production

charm quarks at LHC energies

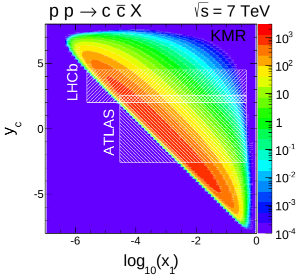
$\Rightarrow$ only gluon-gluon fusion

and very small x-values down to 10^{-5}

great test of many different UGDFs

in so far unexplored kinematical regime

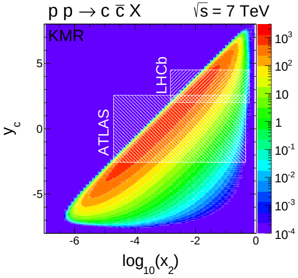
2Dim-differential cross sections for charm quarks $\sqrt{s} = 7$ TeV

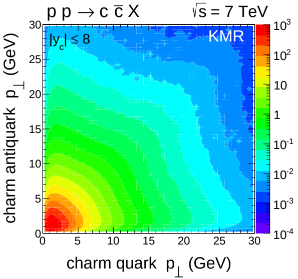


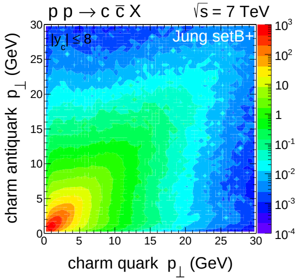
LHC:

$x \gtrsim 10^{-4}$ (ATLAS)

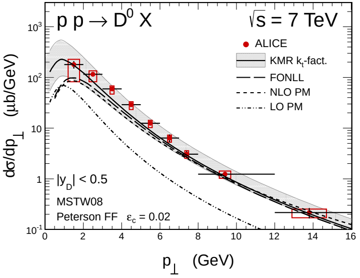
$x \gtrsim 10^{-5}$ (LHCb)

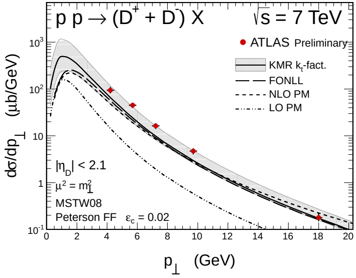


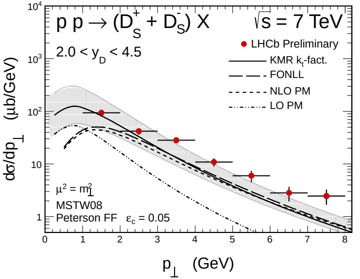




Inclusive D meson spectra ALICE, ATLAS, LHCb

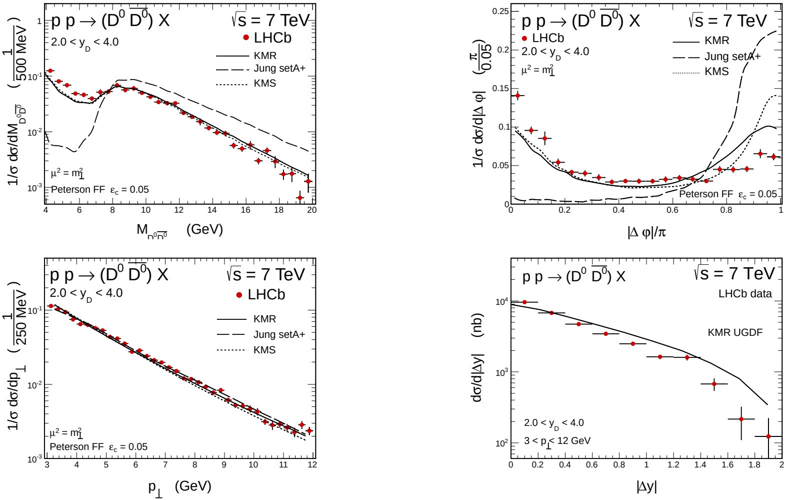






- typical pQCD uncertainties: scales and quark mass
- only the upper limits of uncertainty bands for the KMR UGDF reasonably well describe the ALICE, ATLAS and LHCb data
- k_t-factorization with the KMR UGDF consistent with the FONLL and NLO PM collinear predictions

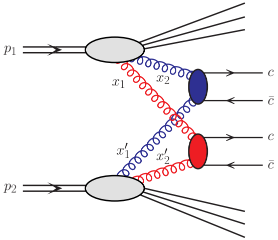
$D\overline{D}$ meson-antimeson correlations vs. LHCb data



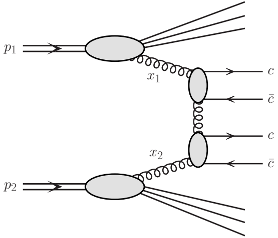
- KMR and KMS UGDFs ⇒ good description of the shapes
- KMR UGDF ⇒ absolute cross section well described

Double charm production (final state with two pairs of $c\bar{c}$)

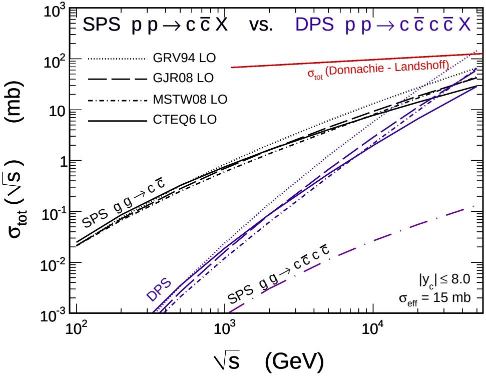
Double-parton scattering (DPS)



Single-parton scattering (SPS)

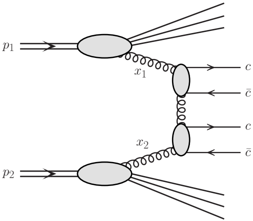


SINGLE CHARM vs. DOUBLE CHARM mechanism

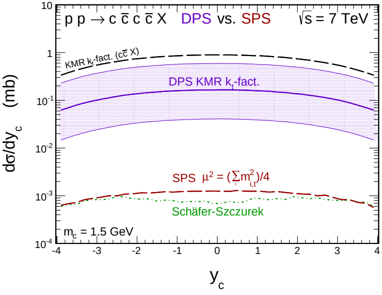


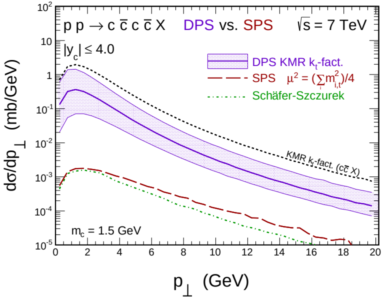
- SPS $c\bar{c}$ vs. DPS $c\bar{c}c\bar{c}$: **comparable total cross sections at LHC energies!**
- SPS $c\bar{c}c\bar{c}$ negligible

Double charm within single-parton scattering

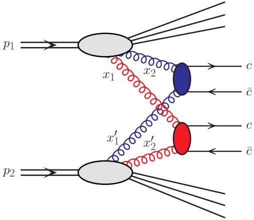


- exact calculations: $gg \to c\bar{c}c\bar{c}$ and $q\bar{q} \to c\bar{c}c\bar{c}$
- LO matrix elements ⇒ color-connected helicity amplitudes
- an automatic program similar to HELAC; a recursive numerical Dyson-Schwinger approach; phase space integration with KALEU, which automatically generates importance sampled phase space points
- high energy approximation ⇒ Schaefer-Szczurek 2012





Simple DPS picture and factorized Ansatz



process initiated by two simultaneous hard gluon-gluon scatterings in one proton-proton interaction $\Rightarrow$

$$\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}} \cdot \sigma^{SPS}(pp \to c\bar{c}X_1) \cdot \sigma^{SPS}(pp \to c\bar{c}X_2)$$

two subprocesses are not correlated and do not interfere

analogy: frequently considered mechanisms of double gauge boson production and double Drell-Yan anihillation

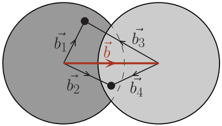
$$\frac{d\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}X_1)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}}$$

in more general form:

$$d\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2} \cdot \Gamma_{gg}(b, x_1, x_2; \mu_1^2, \mu_2^2)\, \Gamma_{gg}(b, x_1', x_2'; \mu_1^2, \mu_2^2)$$
$$\times\, d\sigma_{gg \to c\bar{c}}(x_1, x_2', \mu_1^2) \cdot d\sigma_{gg \to c\bar{c}}(x_1', x_2, \mu_2^2)\; dx_1 dx_2 dx_1' dx_2' d^2b$$

DPDF - emission of one parton with assumption that second parton is also emitted

Double-parton distributions (DPDFs) and factorized Ansatz



$$\Gamma_{i,j}(b, x_1, x_2; \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2)\, F_j(x_2, \mu_2^2)\, F(b; x_1, x_2, \mu_1^2, \mu_2^2)$$

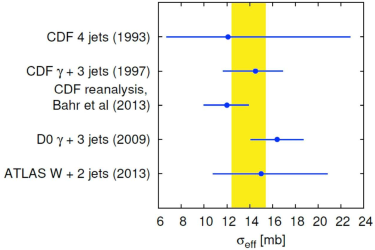
- correlations between two partons
  C. Flensburg et al., JHEP 06, 066 (2011)

in general:

$$\sigma_{eff}(x_1, x_2, x_1', x_2', \mu_1^2, \mu_2^2) = \left(\int d^2b\, F(b; x_1, x_2, \mu_1^2, \mu_2^2)\, F(b; x_1', x_2', \mu_1^2, \mu_2^2)\right)^{-1}$$

factorized Ansatz:

- additional limitations: $x_1 + x_2 < 1$ oraz $x_1' + x_2' < 1$
- DPDF in multiplicative form: $\Gamma_{gg}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_g(x_1, \mu_1^2) F_g(x_2, \mu_2^2) F(b)$
- $\sigma_{eff} = \left[\int d^2b\, (F(b))^2\right]^{-1}$, $F(b)$ - energy and process independent



phenomenology: $\sigma_{eff} \Rightarrow$ nonperturbative quantity with a dimension of cross section, connected with transverse size of proton

$\sigma_{eff} \approx$ **15 mb** ($p_\perp$-independent)

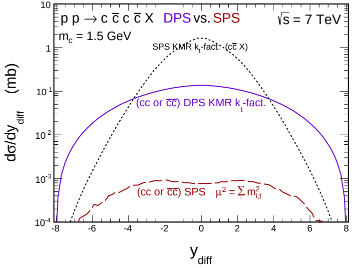
a detailed analysis of σ_{eff}:
Seymour, Siódmok, JHEP 10, 113 (2013)

How the DPS mechanism can be investigated?

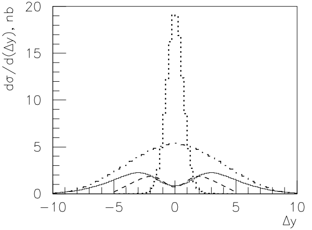
Study of **MESON-MESON pairs** production:

DD pairs - both containing *c* quarks or both containing $\bar{c}$ antiquark

- impossible to produce within standard SPS single $c\bar{c}$ production mechanism
- measurements of charm meson-meson pairs highly recommended at the LHC
- larger rapidity differences between particles: *DD* pairs at ATLAS
- same-sign nonphotonic lepton pairs, e.g. $\mu^+\mu^+$ at ALICE



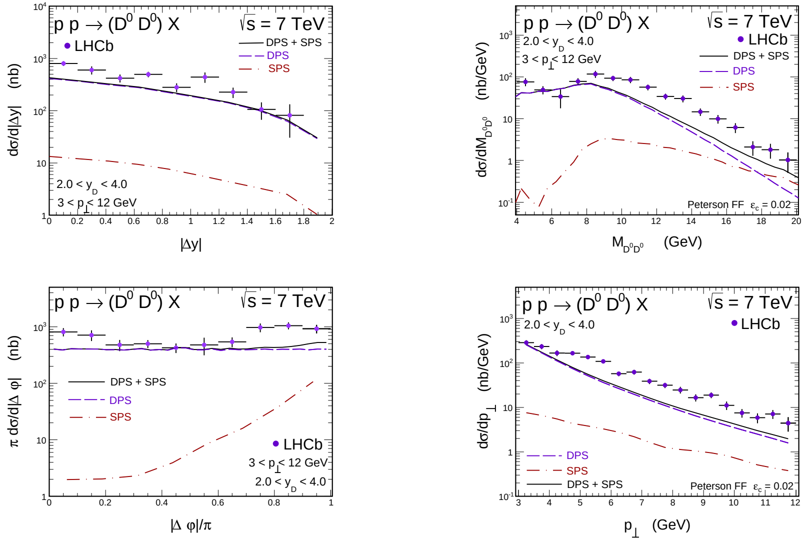
Double open charm ($c\bar{c}c\bar{c}$)



Double hidden charm ($J/\Psi J/\Psi$)

Baranov et al., Phys.Rev. D87, 034035 (2013)

First clean signature of the DPS mechanism?

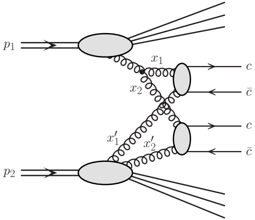


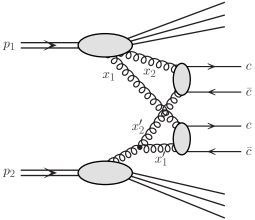
proper order of magnitude but still something is missing (about factor 2)

What can be still missing?

$\sigma(DPS) = \sigma(2v2) + \sigma(2v1)$ → see next talk by J.Gaunt

Different class of the DPS diagrams: 2v1 ⇒ **perturbative parton splitting**





- LO calculations available using splitting DPDFs   J.Gaunt, JHEP 01, 042 (2013)
- J.Gaunt, R.M, A.Szczurek, Phys. Rev. D90, 054017 (2014)
  our first rough estimation: $\frac{DPS(2v1)}{DPS(2v2)} \approx 30-60\%$
- inclusion of the DPS(2v1) contribution in the LHCb data very difficult (pure knowledge of σ_{eff}^{2v1}, σ_{eff}^{2v2}; the LO collinear formalism is not sufficient for charm)
- in the moment more precise calculations, beyond the factorized Ansatz, are very difficult ⇒ more advanced framework has to be worked out

Conclusions

SPS $c\bar{c}$:

- only upper limits of theoretical predictions within the k_t-factorizaton approach give quite reasonable description of the ALICE, ATLAS and LHCb data (also true for FONLL collinear approach)
- k_t-factorizaton approach together with KMR UGDF is very efficient for studying kinematical correlations in less inclusive measurements of $D\bar{D}$ pairs

DPS $c\bar{c}c\bar{c}$:

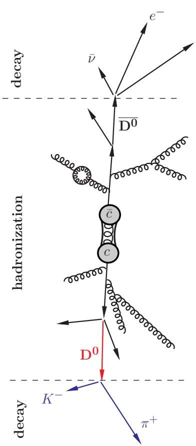
- SPS $c\bar{c}$ and DPS $c\bar{c}c\bar{c}$ cross sections become comparable at LHC energies
- SPS $c\bar{c}c\bar{c}$ mechanism is negligible in comparison to the DPS
- Production of double charm (DD pairs) is an extremely good testing ground of double-parton scattering effects

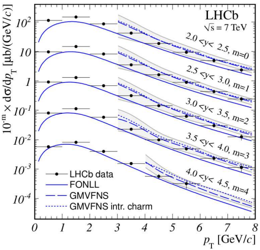
Thank You for attention!

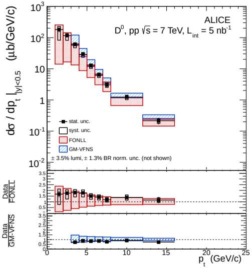
Backup

Heavy quarks measurements in pp scattering at the LHC

- **direct: open charm/bottom mesons** $\rightarrow$ reconstruction of all decay products $(K^-\pi^+, K^+K^-\pi^+, K^-\pi^+\pi^+)$
- indirect: nonphotonic electrons/muons $\rightarrow$ leptons from semileptonic decays of heavy flavoured mesons

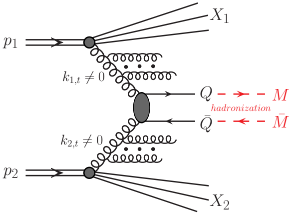






- ALICE, $|y_D| < 0.5$, JHEP 01 (2012) 128; Phys. Lett. B718 (2012) 279
- LHCb, $2.0 < y_D < 4.5$, $p_\perp < 8$ GeV, Nucl. Phys. B871 (2013) 1-20
  very small x region! (down to 10^{-5})
- ATLAS, $|\eta_D| < 2.1$, $p_\perp > 3.5$ GeV, ATLAS-CONF-2011-017
  wide rapidity interval

Fragmentation functions technique



- phenomenology:
  fragmentation functions extracted from e^+e^- data
- often used (older parametrizations):
  Peterson et al., Braaten et al., Kartvelishvili et al.
- more up-to-date: charm nonperturbative fragmentation functions determined from recent Belle, CLEO, ALEPH and OPAL data: **Kneesch-Kniehl-Kramer-Schienbein (KKKS08)** + DGLAP evolution
- FONLL → Braaten et al. (charm) and Kartvelishvili et al. (bottom)
  GM-VFNS → KKKS08 + evolution

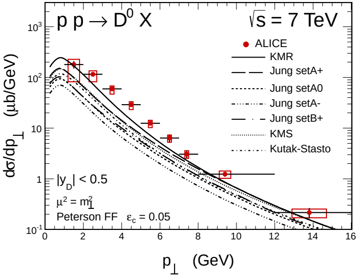
- numerically performed by rescalling transverse momentum at a constant rapidity (angle)
- from heavy quarks to heavy mesons:

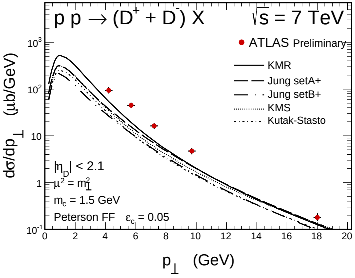
$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q \to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

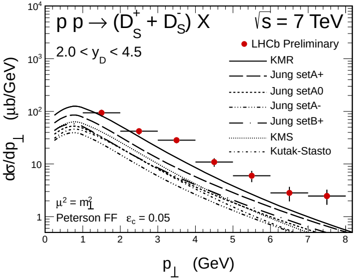
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

- **approximation:**
  rapidity unchanged in the fragmentation process → $y_Q = y_M$

Inclusive *D* meson spectra — ALICE, ATLAS, LHCb







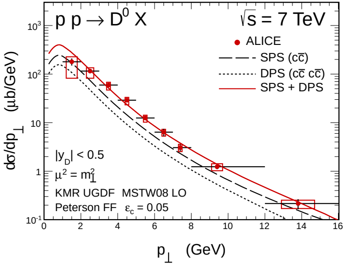
- all of the UGDFs models underestimate experimental data points
- only the KMR UGDF gives results which are close to the measured values

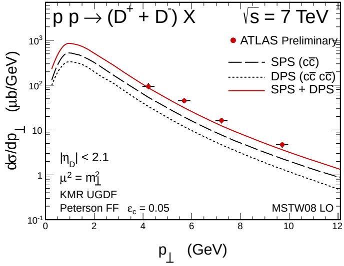
Double charm production: Integrated cross sections

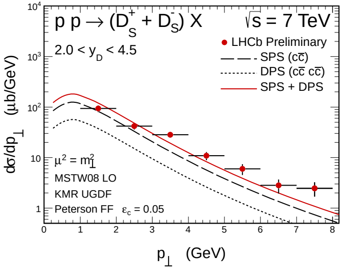
Mode	σ_{tot}^{EXP} (nb)	σ_{tot}^{THEORY} (nb) KMR $^{+}_{-}(\mu)\,^{+}_{-}(m_c)$ $\varepsilon_c = 0.05$	KMR $\varepsilon_c = 0.02$	Jung setA+ $\varepsilon_c = 0.05$	Jung setA+ $\varepsilon_c = 0.02$	KMS $\varepsilon_c = 0.05$	KMS $\varepsilon_c = 0.02$
$D^0 D^0$	$690 \pm 40 \pm 70$	$265\,^{+140}_{-77}\,^{+157}_{-94}$	400	120	175	84	126
$D^0 D^+$	$520 \pm 80 \pm 70$	$212\,^{+112}_{-62}\,^{+126}_{-75}$	319	96	140	67	100
$D^0 D_S^+$	$270 \pm 50 \pm 40$	$75\,^{+40}_{-22}\,^{+45}_{-27}$	113	34	50	24	36
$D^+ D^+$	$80 \pm 10 \pm 10$	$42\,^{+23}_{-13}\,^{+26}_{-15}$	64	19	28	13	20
$D^+ D_S^+$	$70 \pm 15 \pm 10$	$30\,^{+16}_{-9}\,^{+18}_{-11}$	45	14	20	10	14
$D_S^+ D_S^+$	–	$11\,^{+5}_{-3}\,^{+6}_{-4}$	16	5	7	3	5

- σ_{tot}^{THEORY} consistent with experimental values taking into account huge theoretical and experimental uncertainties

Does the DPS contribute to inclusive D mesons spectra?







$$\begin{aligned}\frac{d\sigma_{inc}^{D_i,DPS}}{dp_t} = & \; P_{D_i}(1-P_{D_i})\frac{d\sigma^D}{dp_{1,t}}\Big|_{p_{1,t}=p_t}(-2.1<\eta_1<2.1, -\infty<\eta_2<\infty) \\ & + P_{D_i}(1-P_{D_i})\frac{d\sigma^D}{dp_{2,t}}\Big|_{p_{2,t}=p_t}(-\infty<\eta_1<\infty, -2.1<\eta_2<2.1) \\ & + P_{D_i}P_{D_i}\frac{d\sigma^D}{dp_{1,t}}\Big|_{p_{1,t}=p_t}(-2.1<\eta_1<2.1, -\infty<\eta_2<\infty) \\ & + P_{D_i}P_{D_i}\frac{d\sigma^D}{dp_{2,t}}\Big|_{p_{2,t}=p_t}(-\infty<\eta_1<\infty, -2.1<\eta_2<2.1)\end{aligned}$$