

# Charm mesons in the LHCb fixed-target experiment: phenomenology and production asymmetry

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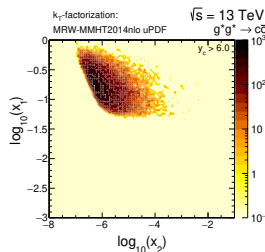
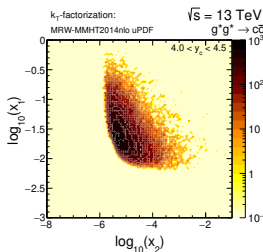
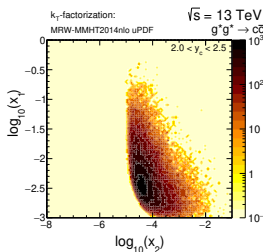


# Far-forward charm production at very high energies

A special kinematic regime: two extreme limits in one observable

- forward rapidity **forces** small- and large- $x$  dynamics simultaneously
- PDFs probed at extremely small ( $x < 10^{-6}$ ) *and* large ( $x > 0.1$ ) momentum fractions

**more forward (larger rapidities)  $\rightarrow$  more asymmetric:** small  $x_2 \times$  large  $x_1$



A reliable description of **forward charm production** (currently affected by large uncertainties) and of the **neutrinos from its decays** is crucial for:

- **collider neutrinos** — far-forward  $\nu$  at the LHC (FASER $\nu$ , SND@LHC) and future FPF; charm constrained *before* extrapolation
- **prompt atmospheric neutrinos** — dominant high-energy QCD background at  $E_\nu \sim 10^5$ – $10^7$  GeV for IceCube, KM3NeT, P-ONE

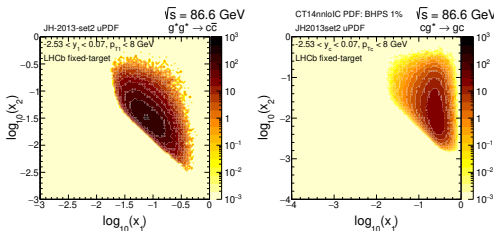
$\hookrightarrow$  also essential for **FCC-hh forward predictions** and for **indirect Dark Matter searches**



# Forward charm production at LHCb in fixed-target mode

Essentially a large- $x$  regime → **only one extreme limit**

- lower energy **removes** the small- $x$  reach: PDFs probed at intermediate ( $10^{-3} < x < 10^{-1}$ ) and large ( $x > 0.1$ ) momentum fractions
- **p+A mode**: LHCb SMOG/SMOG2 with gas targets:  $p\text{He}$ ,  $p\text{Ne}$ ,  $p\text{O}$ ,  $p\text{N}$ ,  $p\text{Ar}$  (important for the interactions in the Earth's atmosphere)



- a clean place to constrain large- $x$  effects (small- $x$  dynamics negligible)
- extra potential effects and mechanisms, enhanced in this regime:
  - **intrinsic charm** in the nucleon
  - **recombination** mechanism

→ also essential for constraining **hadronization** out of the central region

- present models (string fragmentation, cluster models, fragmentation functions) **constrained mainly in central production**
- their extrapolation to forward kinematics is largely untested



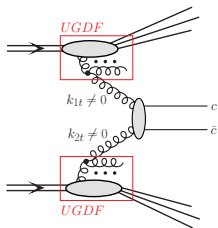
# QCD charm production mechanisms in the forward direction

## Standard production mechanism for heavy flavours:

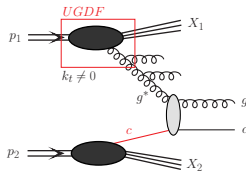
- our default: full  $k_T$ -factorization with off shell initial state partons (and/or hybrid for asymmetric large- $x$ /small- $x$ )
- collinear reference baselines:  
**FONLL (NLO+NLL), aMC@NLO+PS, Pythia 8 (LO+PS)**

## Extra mechanisms, enhanced at large rapidities (forward or backward regions):

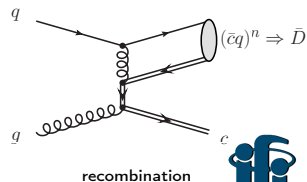
- $g^*c \rightarrow gc \Rightarrow$  the mechanism driven by **the intrinsic charm** component of proton calculated in the hybrid approach with off-shell initial state gluon and collinear intrinsic charm quark
- $gq \rightarrow (\bar{c}q)c \rightarrow \bar{D}c \Rightarrow$  **the recombination mechanism** that takes place before hadronization (leading-order collinear calculations)



standard  $k_T$ -factorization



intrinsic charm  $g^*c \rightarrow gc$



# Charm production driven by the intrinsic charm

What if the proton has a non-perturbative charm content?

## Charm quark in the initial state — two origins:

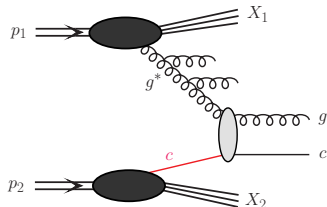
- perturbative: extrinsic charm (from gluon splitting)
- non-perturbative: **intrinsic charm (IC)**
- the differential cross section for the  $cg^* \rightarrow cg$ :

$$d\sigma_{pp \rightarrow \text{charm}}(cg^* \rightarrow cg) = \int dx_1 \int \frac{dx_2}{x_2} \int d^2 k_t$$

$$\times c(x_1, \mu^2) \cdot \mathcal{F}_g(x_2, k_t^2, \mu^2) \cdot d\hat{\sigma}_{cg^* \rightarrow cg}$$

$c(x_1, \mu^2) \Rightarrow$  collinear charm quark PDF (large- $x$ )

$\mathcal{F}_g(x_2, k_t^2, \mu^2) \Rightarrow$  off-shell gluon uPDF (small- $x$ )



## Numerical setup:

- $d\hat{\sigma}_{cg^* \rightarrow cg} \Rightarrow$  only in the massless limit (also available in KaTie)
- phenomenological regularization at  $p_T \rightarrow 0 \Rightarrow$  we adopt the Pythia-like prescription:

$$F_{sup}(p_T) = \frac{p_T^2}{p_{T0}^2 + p_T^2}, \alpha_S(\mu_R^2 + p_{T0}^2), \text{ where } p_{T0} = 1.5 \text{ GeV (free parameter)}$$

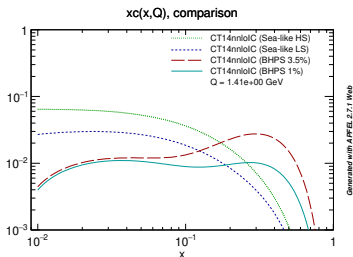
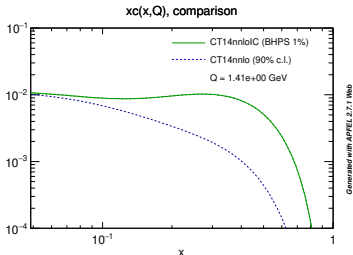
- only the intrinsic component is kept: the charm PDF is taken at the initial scale  $c(x_1, \mu_0^2)$ ,  $\mu_0 = 1.3 \text{ GeV}$ , where the perturbative (extrinsic) charm has not yet been generated



# The concept of intrinsic charm in the nucleon

**Intrinsic charm**  $\Rightarrow$  a non-perturbative  $c\bar{c}$  component, correlated with its valence content

- **pictures:** sea-like vs. valence-like (large- $x$ )
- **realizations we use:**
  - $\rightarrow$  Brodsky-Hoyer-Peterson-Sakai (BHPS):  
parton-level  $|uudc\bar{c}\rangle$  fluctuation
  - $\rightarrow$  Meson-Baryon-Model (MBM):  
hadronic ( $D\Lambda_c$ -type) fluctuation
  - $\rightarrow$  from CT14nnl0C and CT18FC PDFs



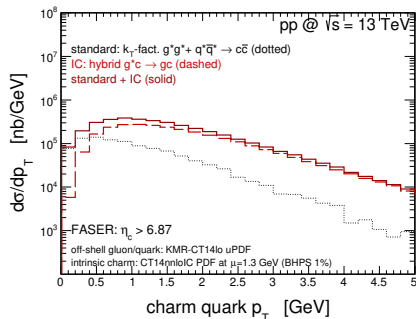
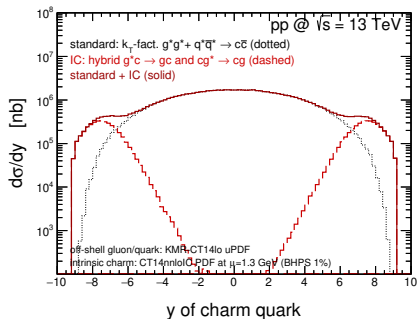
- an intrinsic component leads to a **large enhancement of the charm distribution at large  $x$  ( $> 0.1$ )** compared to the perturbative charm
- but the absolute probability  $P_{ic}$ :
  - $\rightarrow$  is only loosely constrained
  - $\rightarrow$  the models do not fix it (theory gap)
  - $\rightarrow$  global data constrain it only weakly (experimental gap)



# Intrinsic charm at high energy (collider/FASER)

A possible impact of the intrinsic charm component on forward charm production in existing and future experiments at different energies:

- **FASER at the LHC:** forward neutrinos from decays of charm hadrons ( $\nu_e, \nu_\mu$  from  $D^0, D^\pm$  and  $\nu_\tau$  from  $D_s$ )



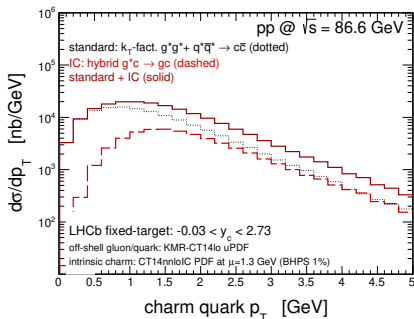
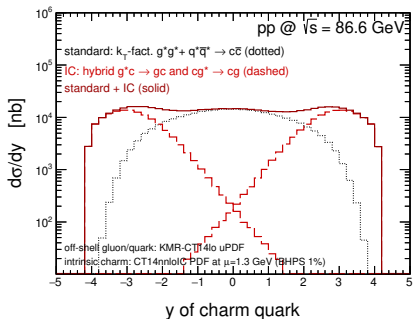
- IC enhances forward charm at  $|y| > 6$  (right in the **FASER** acceptance)
- the  $p_T$  distribution is visibly enhanced (at large  $p_T$  by a factor of 10)



# Intrinsic charm at lower energy (fixed-target)

Same study, lower energy:

- Fixed-target LHCb mode: ( $D$ -meson production)

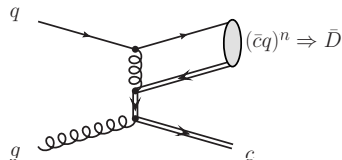


- at lower energy, intrinsic charm shows up **already** at  $|y| > 1$
- in fixed-target kinematics the large- $x$  IC contribution becomes **sizable already within the LHCb acceptance**



# The $c\bar{q}$ -recombination mechanism of charm production

**Braaten-Jia-Mehen (BJM) recombination:**  $q + g \rightarrow (\bar{c}q)^n + c$



- **short-distance process** (in contrast with fragmentation)
- $(\bar{c}q)^n$ :  $q$  has small momentum in the  $\bar{c}$  rest frame
- $q$  and  $\bar{c}$  are in a state with definite color and angular momentum quantum numbers specified by  $n$
- **direct meson**:  $qg \rightarrow \bar{D}c$  and  $\bar{q}g \rightarrow D\bar{c}$
- subsequent fragmentation of the associated  $c$ -quark

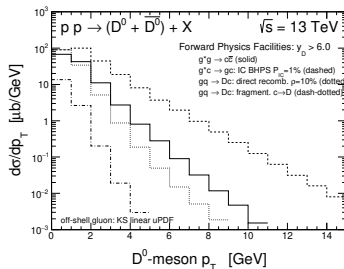
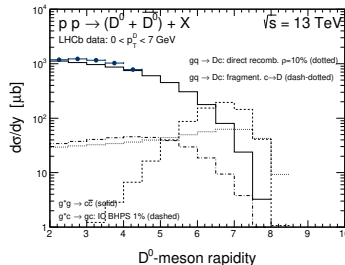
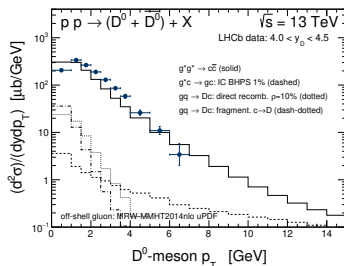
- the differential cross section for  $qg \rightarrow \bar{D}c$  mechanism:

$$\frac{d\sigma}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} [x_1 q_1(x_1, \mu^2) x_2 g_2(x_2, \mu^2) \overline{|\mathcal{M}_{qg \rightarrow \bar{D}c}(s, t, u)|^2} + x_1 g_1(x_1, \mu^2) x_2 q_2(x_2, \mu^2) \overline{|\mathcal{M}_{gq \rightarrow \bar{D}c}(s, t, u)|^2}]$$

- $\overline{|\mathcal{M}_{qg \rightarrow Dc}(s, t, u)|^2} = \overline{|\mathcal{M}_{qg \rightarrow (\bar{c}q)^n c}|^2} \cdot \rho$
- $\overline{|\mathcal{M}_{qg \rightarrow (\bar{c}q)^n c}|^2} \Rightarrow$  explicit form of the matrix element squared available
- $\rho$  can be interpreted as a probability to form real meson  
 $\Rightarrow$  can be extracted from experimental data



# The $c\bar{q}$ -recombination mechanism of charm production



- both IC and recombination **negligible** at the LHCb in collider mode:  
 $\sqrt{s} = 13 \text{ TeV}$ ,  $2 < y < 4.5$
- situation changes when approaching larger rapidities
- $y > 6$ : IC dominates over the standard mechanism
- $y > 6$ : recombination and the standard mechanism **of similar size**

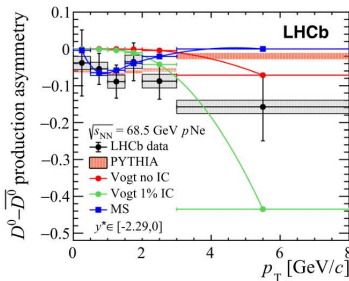
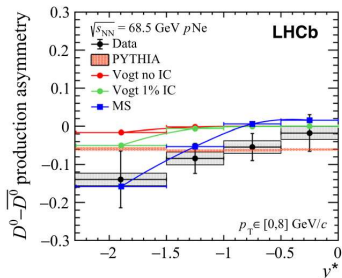


# Charm-anticharm asymmetry in fixed-target data

**Recombination is enhanced in the forward / backward region** — where the charm quark recombines with valence partons of the projectile or target

- just like intrinsic charm: at lower  $\sqrt{s}$  the large- $x$  recombination region shifts to **smaller rapidity, within the LHCb acceptance**
- recombination leads to a sizeable  $D/\bar{D}$  **production asymmetry** driven by the proton's  $u/\bar{u}$ ,  $d/\bar{d}$  asymmetry
- such an asymmetry has been **measured by LHCb** in  $p$ Ne fixed-target at  $\sqrt{s_{NN}} = 68.5$  GeV (EPJC 83 (2023) 541)

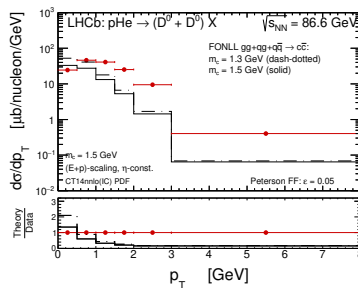
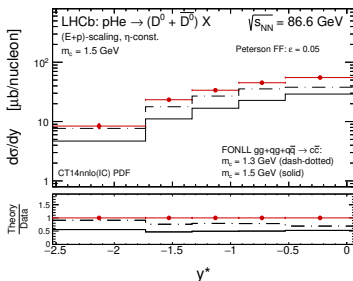
↪ a good observable to **constrain**  $\rho$  and maybe to disentangle recombination contribution from intrinsic charm



# LHCb fixed-target charm vs FONLL

Some problems with understanding the LHCb fixed-target open charm data

- baseline: **FONLL** (fixed-order NLO + NLL) + Fragmentation Function (FF)
- data:  $p\text{He} \rightarrow (D^0 + \bar{D}^0)X$  at  $\sqrt{s_{NN}} = 86.6$  GeV



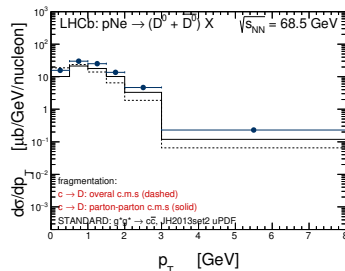
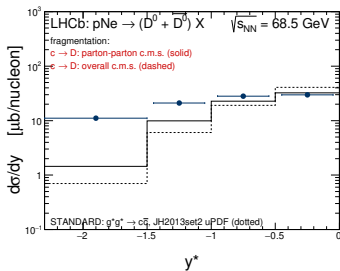
- **fails** for the  $p_T$  spectrum: the data points far above the prediction at large  $p_T$
- in rapidity, **only the upper edge** of the theory band reaches the data
- even spanning all uncertainties (charm mass,  $\mu_R/\mu_F$  scales, PDFs, fragmentation), the band does not cover the data



# LHCb fixed-target charm vs $k_T$ -factorization

Some problems with understanding the LHCb fixed-target open charm data

- baseline:  **$k_T$ -factorization** (LO + CCFM uPDF) + Fragmentation Function (FF)
- data:  $p\text{Ne} \rightarrow (D^0 + \bar{D}^0)X$  at  $\sqrt{s_{NN}} = 68.5$  GeV



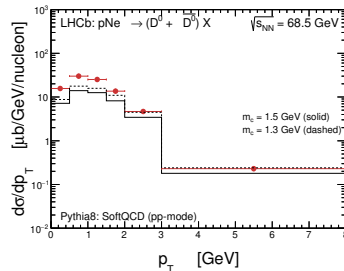
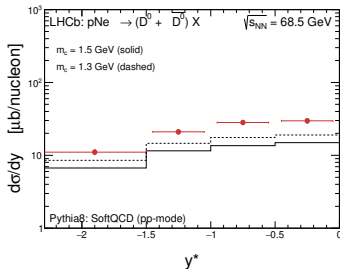
- **fails** at large  $p_T$  and backward rapidities
- the FF procedure is limited in **forward production and at low  $p_T$**  (e.g. the usual midrapidity approximation  $y_c = y_D$  is not valid here)
- **our update**: fragmentation performed in the **parton-parton c.m.s.** (solid), not the overall  $pp$  c.m.s. (dashed)  $\Rightarrow$  a **visible sensitivity** to the FF details
- even with this update, **fragmentation remains the most uncertain ingredient** of the model (to be treated with caution)



# LHCb fixed-target charm vs Pythia 8

*Some problems with understanding the LHCb fixed-target open charm data*

- baseline: **Pythia 8** (LO + PS) + default hadronization
- data:  $p\text{Ne} \rightarrow (D^0 + \bar{D}^0)X$  at  $\sqrt{s_{NN}} = 68.5$  GeV



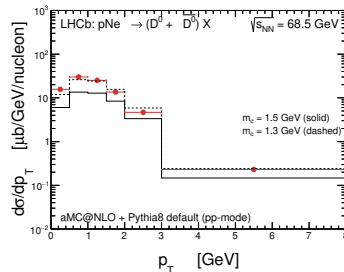
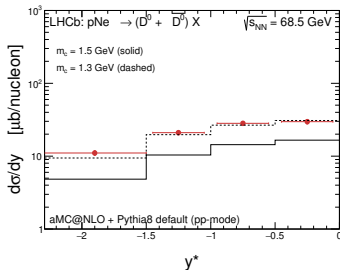
- **underestimates the data** in rapidity (over the whole range) and at small  $p_T$
- shown for two charm masses,  $m_c = 1.5$  GeV (solid) and 1.3 GeV (dashed)
- a default (central-production) tune: **string hadronization and colour reconnection not constrained in the forward region**
- dedicated forward physics tunes needed  
(some first attempts done only very recently in Phys.Rev.D 109 (2024) 1, 016010)



# LHCb fixed-target charm vs aMC@NLO + PS

Some problems with understanding the LHCb fixed-target open charm data

- baseline: **aMC@NLO+PS** + default hadronization (Pythia 8)
- data:  $p\text{Ne} \rightarrow (D^0 + \bar{D}^0)X$  at  $\sqrt{s_{NN}} = 68.5$  GeV



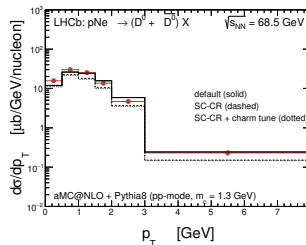
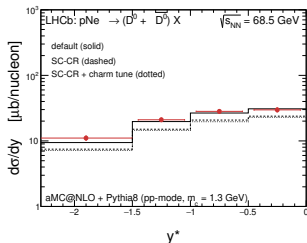
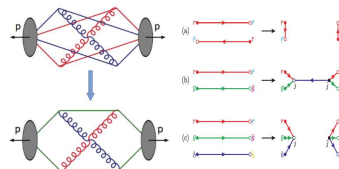
- the **most complete standard approach** (NLO matrix element + shower + hadronization)
- with  $m_c = 1.3$  GeV (dashed) the data are described **markedly better** but this is effectively an **upper limit**
- for the standard  $m_c = 1.5$  GeV (solid) the description is **clearly worse**
- all results use the **default colour-reconnection (CR) model** (MPI-based); significant progress in this area has been made recently



# Improving hadronization: aMC@NLO+PS with QCD-CR

## Beyond the default colour reconnection: QCD-CR

- partons produced in perturbative scatterings are colour connected;
- assuming nature prefers minimization of the net string length, the colour dipoles interact with each other **at colour reconnection stage**
- at this stage, colour dipoles rearrange to shorter dipoles with a probability of 1/9 (default CR)
- new configurations (junctions) allowed in a QCD colour-algebra based CR and they have additional contributions to baryon production

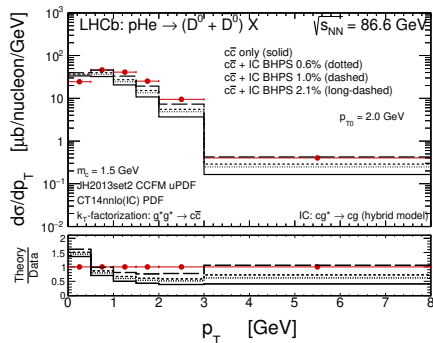
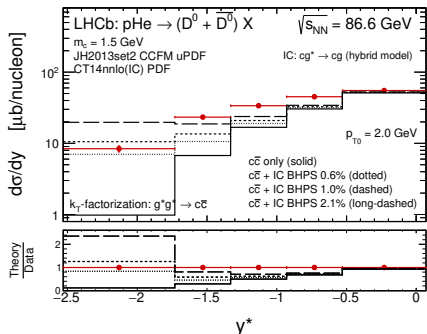


- QCD-CR shifts charm from mesons into baryons** (junction effect)  $\Rightarrow$  the  $D$ -meson yield drops **visibly below the data** (even for aMC@NLO+PS,  $m_c = 1.3$  GeV)
- a more advanced hadronization model **redistributes** charm
- the charm meson deficit points to a need of **forward tune** or to a **missing production mechanisms** (or both)



# How to improve description of the data?

- a new scenario proposed with the intrinsic charm contribution needed to describe the data points in the backward direction and at larger  $p_T$ 's

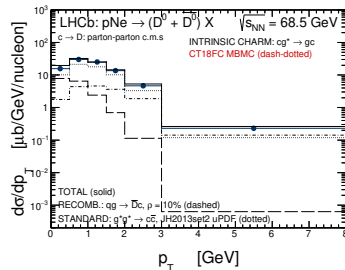
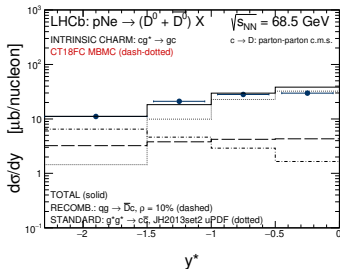


- improvement strongly dependent on the  $P_{ic}$  parameter
- CT14nnloIC PDF + old fragmentation procedure
- $P_{ic} \approx 1.65\%$  (upper limit)



# How to improve description of the data?

- Mixed scenario: IC (dash-dotted) + 10% recombination (dashed)
- recombination contributes mostly at small transverse momenta and is especially important for the most backward rapidity bin

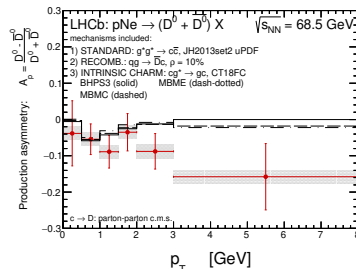
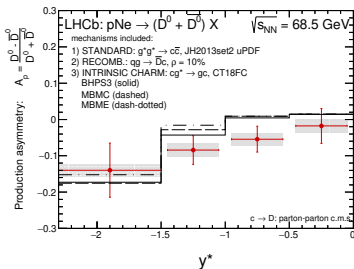


- new fragmentation procedure (parton-parton c.m.s.)
- CT18FC: BHPS and MBM (both models lead to very similar distributions)
- $P_{IC} \approx 0.5\%$  (upper limit)



# $D/\bar{D}$ asymmetry: LHCb fixed-target at $\sqrt{s} = 68.5$ GeV

- BHPS3: symmetric  $c = \bar{c}$
- MBMC/MBME: asymmetric  $c \neq \bar{c} \Rightarrow$  may lead to  $D/\bar{D}$  production asymmetry

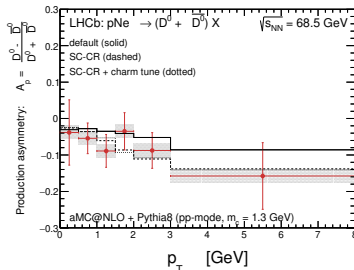
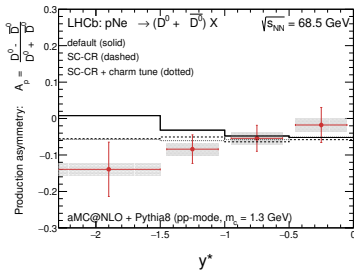


- backward rapidity region and small- $p_T$ : the asymmetry well described by the recombination (the asymmetric IC does not change the situation here)
- the asymmetry at larger  $p_T$ 's: cannot be described by the recombination
- asymmetric IC generates the  $D/\bar{D}$  asymmetry at large- $p_T$ , however, the effect is too small to describe the data points



# $D/\bar{D}$ asymmetry: LHCb fixed-target at $\sqrt{s} = 68.5$ GeV

- Colour reconnection (QCD-CR) **does influence the asymmetry**



- including **QCD-CR** (SC-CR, dashed/dotted) has a **clear effect on the asymmetry** — it moves the predictions **closer to the LHCb data**
  - **fully accounts** for the **asymmetry at large  $p_T$** , but **not enough at backward rapidities** (most negative  $y^*$  bin still missed)
- ↪ points to a possible **coexistence of all three effects** — recombination, intrinsic charm and QCD-CR (**work in progress**)



# Conclusions

We have shown that **intrinsic charm** and **recombination** can be extremely important for **forward charm production** at energies much lower than the nominal LHC energies:

## *D* mesons at the fixed-target LHCb experiment

- a scenario is proposed in which the intrinsic charm contribution is needed to describe the data points in the backward direction and at larger  $p_T$
  - an upper limit on the intrinsic charm probability  $P_{IC}$  ( $\approx 0.5\%$ ) with CT18FC
  - still room for the recombination mechanism ( $\approx 10\%$ )
  - the recombination probability extracted from the  $D/\bar{D}$  production asymmetry
  - the  $D/\bar{D}$  asymmetry in the backward region and at small transverse momenta is well described by the recombination mechanism
  - the asymmetry at larger transverse momenta is described neither by the recombination mechanism nor by the asymmetric intrinsic charm
  - the inclusion of **QCD colour reconnection** accounts for the large- $p_T$  asymmetry, though it remains insufficient at backward rapidities
- ↪ most likely a **coexistence** of intrinsic charm, recombination and QCD-CR  
**(work in progress)**

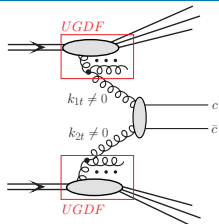
Thank You!



## Backup Slides



# The $k_T$ -factorization approach



## off-shell initial state partons $\Rightarrow$

initial transverse momenta explicitly included  $k_{1,t}, k_{2,t} \neq 0$

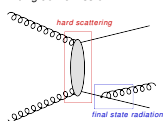
- additional hard dynamics coming from transverse momenta of incident partons (virtualities taken into account)
- very efficient for less inclusive studies of kinematical correlations
- more exclusive observables, e.g. pair transverse momentum or azimuthal angle very sensitive to the incident transverse momenta

multi-differential cross section:

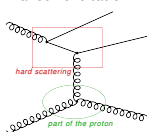
$$\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \int \frac{d^2 k_{1,t}}{\pi} \frac{d^2 k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{g^* g^* \rightarrow Q\bar{Q}}|^2} \times \delta^2(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) \mathcal{F}_g(x_1, k_{1,t}^2, \mu) \mathcal{F}_g(x_2, k_{2,t}^2, \mu)$$

- the LO off-shell matrix elements  $\overline{|\mathcal{M}_{g^* g^* \rightarrow Q\bar{Q}}|^2}$  available (analytic form)
- the  $2 \rightarrow 3$  and  $2 \rightarrow 4$  real emissions (tree-level, KaTie MC)
- $\mathcal{F}_g(x, k_t^2, \mu)$ : transverse momentum dependent; unintegrated PDFs (uPDFs/UGDFs)

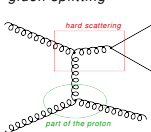
pair creation with gluon emission



flavour excitation



gluon splitting



- part of higher-order (real) corrections is partially included in uPDF



# The quark to meson transition

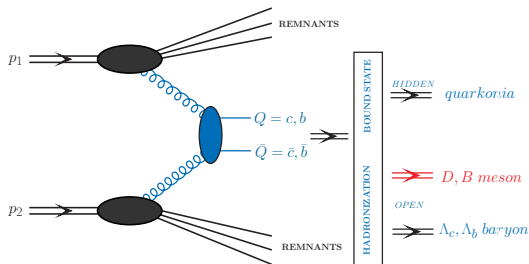
## Heavy quark to open heavy meson fragmentation: $c \rightarrow D$ and $\bar{c} \rightarrow \bar{D}$

The independent parton fragmentation picture:

- the charmed meson  $x_F$ -distributions at large  $x_F$  can be obtained from the charm quark/antiquark  $x_F^c$ -distributions as:

$$\frac{d\sigma_{pp \rightarrow D}(x_F)}{dx_F} = \int_{x_F}^1 \frac{dz}{z} \frac{d\sigma_{pp \rightarrow charm}(x_F^c)}{dx_F^c} D_{c \rightarrow D}(z),$$

- where  $x_F^c = x_F/z$  and  $D_{c \rightarrow D}(z)$  is the relevant fragmentation function (FF)
- the fragmentation procedure leads to a decrease of the  $x_F$  range for meson with respect to  $x_F^c$  of the parent quark

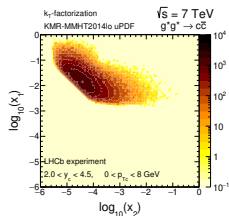


- $c \rightarrow D$ : Peterson( $z$ ),  $\varepsilon = 0.05$  (well known from  $e^+e^-$  data)
- $\eta_D = \eta_c$ ,  $x_F = z \cdot x_F^c$ ,  $z \in (0, 1)$
- fragmentation fractions well known (Particle Data Group)



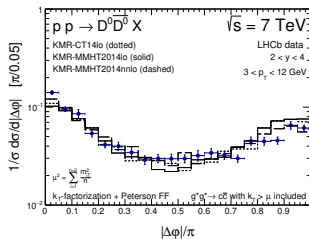
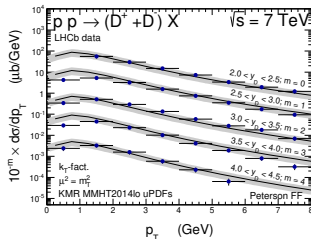
# Forward charm production at the LHCb in collider mode

## Open charm LHCb data in $pp$ -scattering at $\sqrt{s} = 7, 13$ TeV:



Detector acceptance:  $2.0 < y < 4.5$  and  $0 < p_T < 8$  GeV

- inclusive  $D$ -meson spectra and  $D\bar{D}$ -pair correlation observables ( $M_{inv}, \Delta\varphi, p_T$ -pair)
- longitudinal momentum fractions probed:  
 $10^{-3} < x_1 < 10^{-1}$  and  $10^{-5} < x_2 < 10^{-3}$
- $p_T$ -differential cross section well described in different  $y$ -bins
- correct shapes of the correlation observables



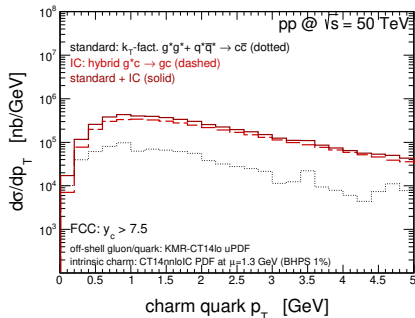
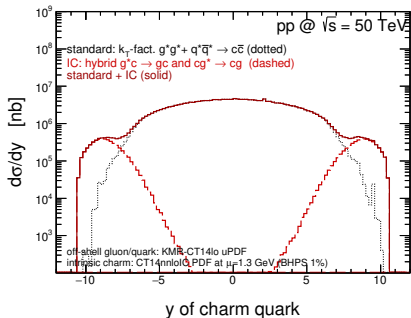
- $k_T$ -factorization works very well in the collider mode (high energy, small- $x$ )  
 $\hookrightarrow$  validated here  $\Rightarrow$  used as the **baseline for the lower-energy fixed-target studies**



# Intrinsic charm at the LHC and beyond

A possible impact of the intrinsic charm component on the forward charm particle production in already existing or future experiments at different energies:

- **Future Circular Collider (FCC)** (*D*-meson production)



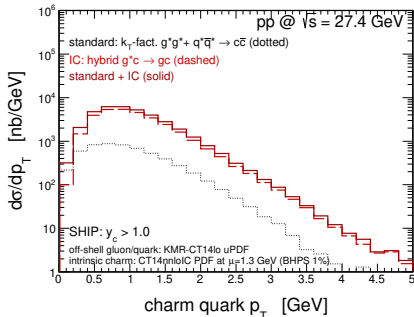
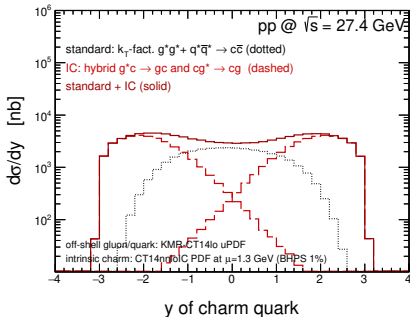
- the intrinsic charm important at  $|y| > 7$
- transverse momentum distribution visibly enhanced



# Intrinsic charm at the LHC and beyond

A possible impact of the intrinsic charm component on the forward charm particle production in already existing or future experiments at different energies:

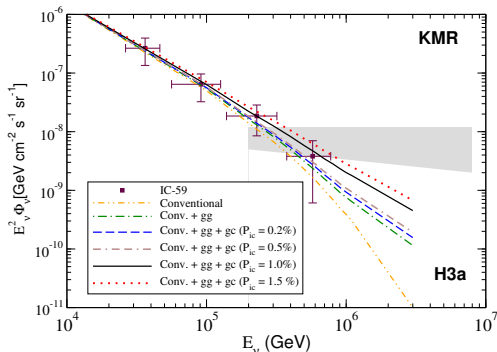
- SHIP/DsTau at the SPS CERN at  $\sqrt{s} = 27.4$  GeV (dedicated to a measurement of forward  $\nu_\tau$  neutrinos originating from semileptonic decays of  $D_s$  mesons)



- at the lower energy  $\Rightarrow$  the intrinsic charm important in the whole rapidity spectrum
- transverse momentum distribution visibly enhanced



# IceCube: Predictions and limits for intrinsic charm



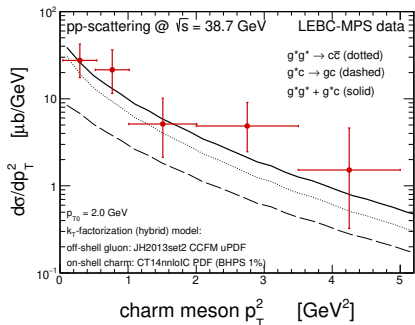
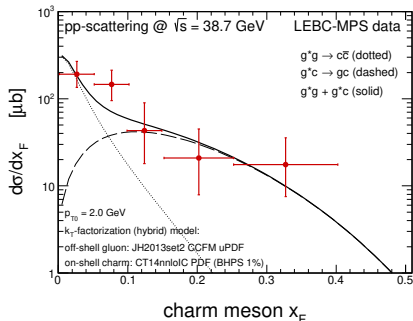
- the impact of the prompt flux is small in the current kinematical range probed by IceCube as long as only the gluon-gluon fusion mechanism is taken into account
- the intrinsic charm mechanism implies a large enhancement of the prompt flux at large  $E_\nu$ , with the associated magnitude being dependent on the value of  $P_{ic}$
- linear QCD dynamics  $\Rightarrow P_{ic} \leq 1.5\%$
- similar to the central CT14nnloIC PDF set



# Fixed-target charm data at $\sqrt{s} = 38.7$ GeV: Intrinsic Charm

The fixed-target data on forward open charm meson production already exists:

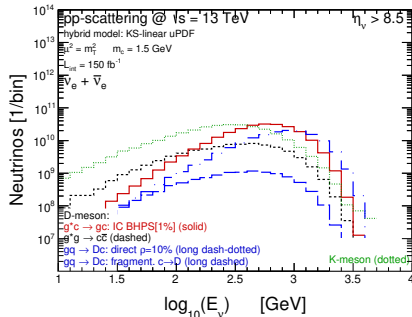
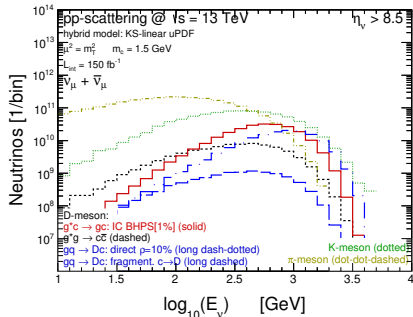
- Fermilab (1986):  $D$ -meson production in  $pp$ -scattering at  $\sqrt{s} = 38.7$  GeV



- we obtain a very good description of the  $x_F$ -distribution within our model with the same set of parameters as in the LHCb case
- the intrinsic charm crucial for large- $x_F$  data



# FASER $\nu$ 2: Far-forward neutrino fluxes

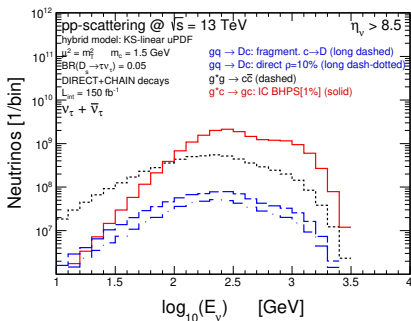


## Semileptonic decays of $D^0, D^+, \Lambda_c \Rightarrow$ source of $\nu_e, \nu_\mu$

- $E_\nu > 100$  GeV  $\Rightarrow$  intrinsic charm and recombination larger than standard mechanism
- both IC and recombination of similar size
- $\nu_\mu$ : large backgrounds from  $\pi$  and  $K$   
 $\Rightarrow$  IC and recombination completely covered even at large energies
- $\nu_e$ : large background from  $K$  but  
 $\Rightarrow$  both IC and recombination win at  $E_\nu > 1000$  GeV



# FASER $\nu$ 2: Far-forward neutrino fluxes

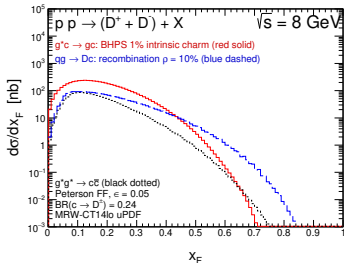
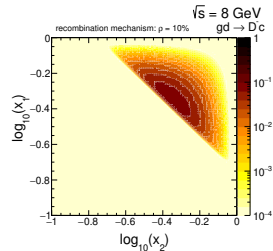
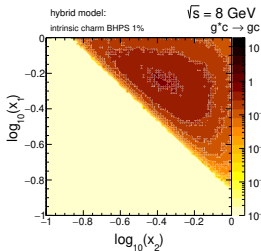
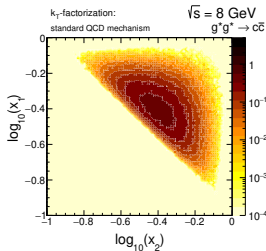


## $D_s^+$ meson decays $\Rightarrow$ dominant source of $\nu_\tau$

- direct  $D_s^+ \rightarrow \tau^+ \nu_\tau$  and chain  $D_s^+ \rightarrow \tau^+ \rightarrow \bar{\nu}_\tau$  decays
- no background from light mesons due to limited phase space for  $\tau$  production in the  $D_s$  decay
- $s(x) \ll u_{val}(x), d_{val}(x) \Rightarrow$  recombination reduced
- $E_\nu > 100$  GeV  $\Rightarrow$  intrinsic charm larger than standard mechanism
- flux dominated by intrinsic charm
- optimal to pin down the IC contribution in the nucleon



# What if we go to even lower energies?



- probing of parton distributions at very large- $x$
- the cross section  $\Rightarrow$  tens of nanobarns
- different production mechanisms  $\Rightarrow$  both intrinsic charm and recombination sizeable
- **WARNING:** large uncertainties from the perturbative calculations (different approaches, charm quark mass, scales) and from non-perturbative hadronization (differences in charm hadronization in  $pp$  and  $e^+e^-$ ;  $\Lambda/D$  enhancement; hadronization in central regions and in forward directions, etc.)
- SIS100 (CBM, NuStar) can contribute?

