Production of charm and neutrinos in far-forward experiments at the LHC

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based on:
Phys.Rev.D 107, 034002 (2023); Phys.Lett.B 835, 137530 (2022),
Phys.Rev.D 105, 014001 (2022); Eur.Phys.J.C 82, 3, 236 (2022),
Phys. Rev. D96 (2017) 9, 094026

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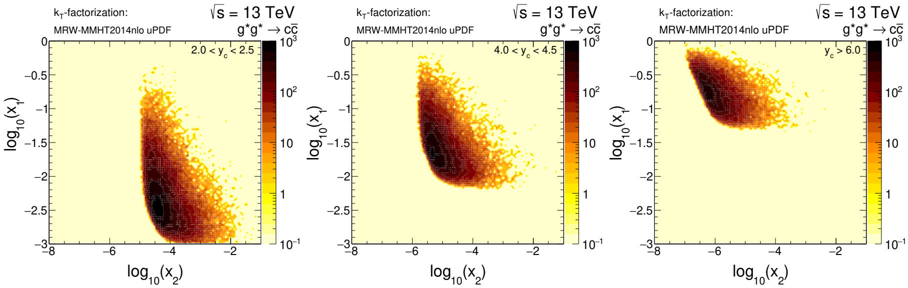
Far-forward charm production at high energies

- an interplay of small- and large-x effects
- probing parton densities simultaneously at extremely small ($x < 10^{-6}$) and large ($x > 0.1$) longitudinal momentum fractions



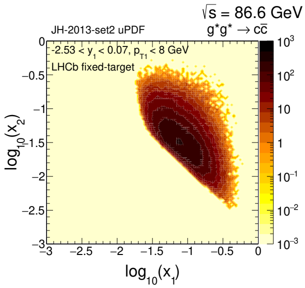
- gluon saturation, intrinsic charm content of the nucleon, recombination mechanism
- forward hadronization (subleading fragmentation, color reconnection, beyond leading color strings, etc.)

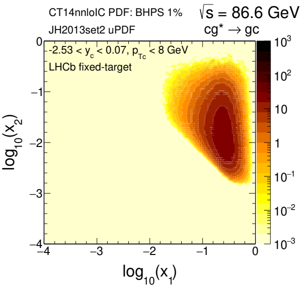
Experiments connected to forward charm production at the LHC and beyond:

- Forward Physics Facilities (FPF) at the LHC: (FASERν, FASERν2, SND@LHC, FLArE): ν_e, ν_μ, ν_τ neutrino fluxes
- IceCube Neutrino Observatory: prompt ν_μ neutrino flux

Forward charm production at low energies

- rather large-x effects
- probing parton densities simultaneously at rather intermediate ($x \gtrsim 10^{-3}$) and large ($x \gtrsim 0.1$) longitudinal momentum fractions



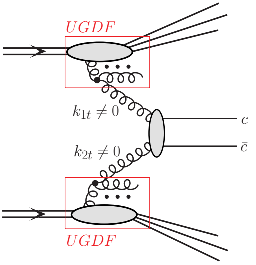


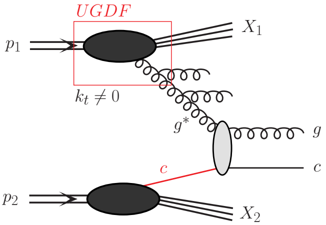
- ~~gluon saturation~~, intrinsic charm content of the nucleon, recombination mechanism
- forward hadronization (subleading fragmentation, color reconnection, beyond leading color strings, etc.)

Experiments connected to forward charm production at lower energies:

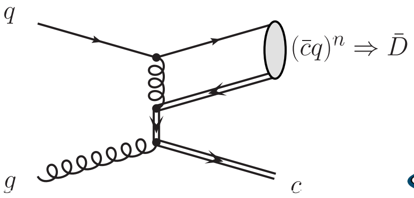
- fixed-target LHCb mode: D-meson, J/Ψ-meson at $\sqrt{s} = 86.6$ GeV and 68.5 GeV
- fixed-target SHIP experiment at SPS: ν_τ neutrino flux $\sqrt{s} = 27.4$ GeV
- fixed-target NA69/DsTau experiment at SPS: ν_τ neutrino flux $\sqrt{s} = 27.4$ GeV

QCD charm production mechanisms at forward directions

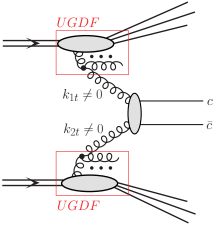




- $g^* g^* \to c\bar{c}$ ⇒ **the standard QCD mechanism** (and usually considered as a leading) of gluon-gluon fusion with off-shell initial state partons, calculated both in the full k_T-factorization approach and in the hybrid model
- $g^* c \to gc$ ⇒ the mechanism driven by **the intrinsic charm** component of proton calculated in the hybrid approach with off-shell initial state gluon and collinear intrinsic charm quark
- $gq \to \overline{D}c$ ⇒ **the recombination mechanism** calculated in the leading-order collinear approach



The k_T-factorization (high-energy factorization) approach



off-shell initial state partons $\Rightarrow$

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

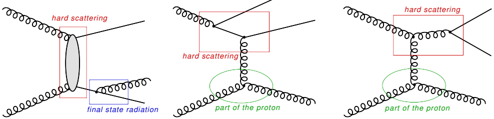
- additional hard dynamics coming from transverse momenta of incident partons (virtualities taken into account)
- very efficient for less inclusive studies of kinematical correlations
- more exclusive observables, e.g. pair transverse momentum or azimuthal angle very sensitive to the incident transverse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

multi-differential cross section:

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

- the LO off-shell matrix elements $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$ available (analytic form)
- the $2 \to 3$ and $2 \to 4$ processes (higher-order) only at tree-level (KaTie Monte Carlo)
- $\mathcal{F}_g(x, k_t^2, \mu)$ - transverse momentum dependent - unintegrated PDFs (uPDFs)

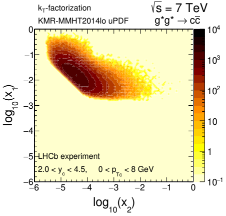
pair creation with gluon emission — *flavour excitation* — *gluon splitting*



- part of higher-order (real) corrections might be effectively included in uPDF

Forward open charm production at the LHCb

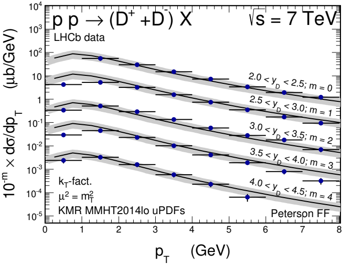
Open charm LHCb data in *pp*-scattering at $\sqrt{s}$ =7, 13 TeV:

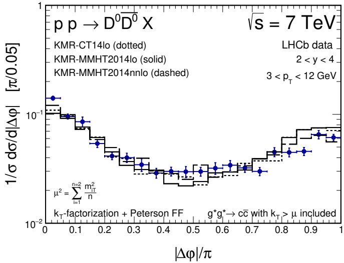


Detector acceptance: $2.0 < y < 4.5$ and $0 < p_T < 8$ GeV

- inclusive D-meson spectra and $D\overline{D}$-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

(R.M., A. Szczurek, Phys.Rev.D 100 (2019) 5, 054001)

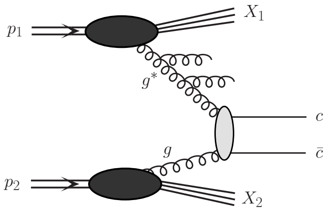




- k_T-factorizaton: $g^*g^* \to c\bar{c}$ + KMR uPDF $\Rightarrow$ works very well

Moving more forward: The hybrid factorization

How to treat theoretically the asymmetric configuration?



The hybrid approach for far-forward production ⇒

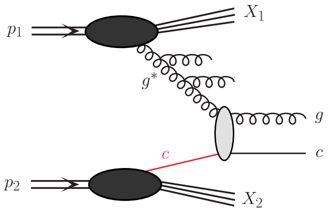
- combined collinear- and k_T-factorization
- used in many phenomenological studies
- the differential cross section for $gg^* \to c\bar{c}$ mechanism:

$$d\sigma_{pp\to charm}(gg^* \to c\bar{c}) = \int dx_1 \int \frac{dx_2}{x_2} \int d^2k_t \times g(x_1,\mu^2) \cdot \mathcal{F}_g(x_2,k_t^2,\mu^2) \cdot d\hat{\sigma}_{gg^*\to c\bar{c}}$$

- $g(x_1,\mu^2)$ ⇒ collinear large-x gluon
  we use the CT14nnlo PDF
- $\mathcal{F}_g(x_2,k_t^2,\mu^2)$ ⇒ off-shell small-x gluon
  we use the KMR/MRW and the KS linear/nonlinear uPDFs
- $d\hat{\sigma}_{gg^*\to c\bar{c}}$ is the hard partonic cross section obtained from a gauge invariant off-shell tree-level amplitudes (available in KaTie)
- a derivation of the hybrid factorization from the dilute limit of the Color Glass Condensate approach can be found in the literature

Charm production driven by the intrinsic charm

What if there is a non-perturbative charm content of the proton?



The charm quark in the initial state ⇒

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

$$d\sigma_{pp\to charm}(cg^* \to cg) = \int dx_1 \int \frac{dx_2}{x_2} \int d^2k_t$$
$$\times\, c(x_1, \mu^2) \cdot \mathcal{F}_g(x_2, k_t^2, \mu^2) \cdot d\hat{\sigma}_{cg^*\to cg}$$

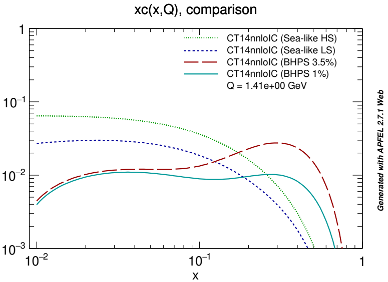
- $c(x_1, \mu^2)$ ⇒ collinear charm quark PDF (large-x)
- $\mathcal{F}_g(x_2, k_t^2, \mu^2)$ ⇒ off-shell gluon uPDF (small-x)

- $d\hat{\sigma}_{cg^*\to cg}$ ⇒ only in the massless limit (also available in KaTie)
- regularization needed at $p_T \to 0$ ⇒ we use PYTHIA prescription:
  $F_{sup}(p_T) = \frac{p_T^2}{p_{T0}^2 + p_T^2}$, $\alpha_S(\mu_R^2 + p_{T0}^2)$, where $p_{T0} = 1.5$ GeV (free parameter)
- the charm quark PDF with IC content is taken at the initial scale: $c(x_1, \mu_0^2)$, where $\mu_0 = 1.3$ GeV so the perturbative charm contribution is intentionally not taken into account

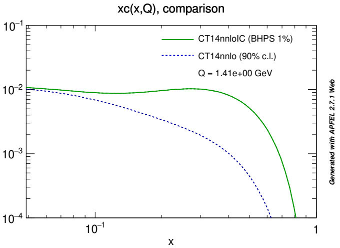
The concept of intrinsic charm in the nucleon

The intrinsic charm quarks ⇒ multiple connections to the valence quarks of the proton

- strong evidence for internal strangeness and somewhat smaller for internal charm



- global experimental data put only loose constraints on the P_{ic} probability
- dfferent pictures of non-perturbative $c\bar{c}$ content:
  - sea-like models
  - valence-like models
- we use the IC distributions from the Brodsky-Hoyer-Peterson-Sakai (BHPS) model as adopted in the CT14nnloIC PDF

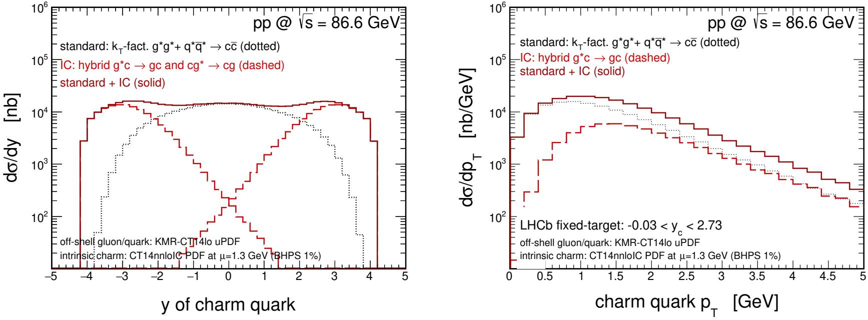


- the presence of an intrinsic component implies a large enhancement of the charm distribution at large x (>0.1) in comparison to the extrinsic charm prediction
- the models do not allow to predict precisely the absolute probability P_{ic}

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:
(R.M, A. Szczurek, JHEP 10 (2020) 135)

- Fixed-target LHCb mode at $\sqrt{s} = 86.6$ GeV (D-meson production)

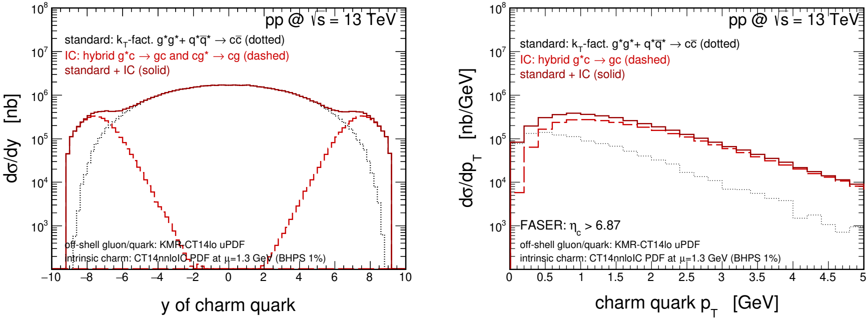


- at the lower energy $\Rightarrow$ the intrinsic charm important already at $|y| > 1$

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:
(R.M, A. Szczurek, JHEP 10 (2020) 135)

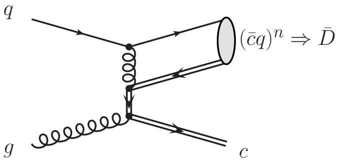
- FASER at the LHC (dedicated to a measurement of forward neutrinos originating from semileptonic decays of D mesons)



- the intrinsic charm important at $|y| > 6$
- transverse momentum distribution visibly enhanced

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

Braaten-Jia-Mechen (BJM) recombination: $q + g \to (\bar{c}q)^n + c$



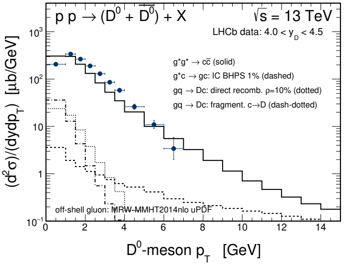
- short-distance process (in contrast with fragmentation)
- $(\bar{c}q)^n$: q has small momentum in the $\bar{c}$ rest frame
- q and $\bar{c}$ are in a state with definite color and angular momentum quantum numbers specified by n
- direct meson: $qg \to \bar{D}c$ and $\bar{q}g \to D\bar{c}$
- subsequent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

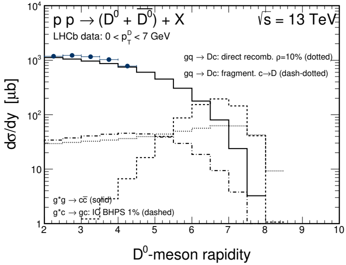
- the differential cross section for $qg \to \bar{D}c$ mechanism:

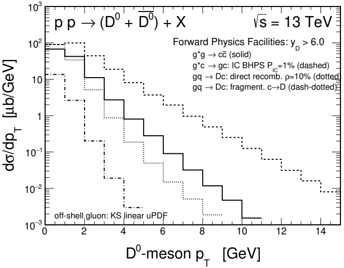
$$\frac{d\sigma}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2}[x_1 q_1(x_1,\mu^2)\, x_2 g_2(x_2,\mu^2)\overline{|\mathcal{M}_{qg\to\bar{D}c}(s,t,u)|^2} + x_1 g_1(x_1,\mu^2)\, x_2 q_2(x_2,\mu^2)\overline{|\mathcal{M}_{gq\to\bar{D}c}(s,t,u)|^2}]$$

- $\overline{|\mathcal{M}_{qg\to Dc}(s,t,u)|^2} = \overline{|\mathcal{M}_{qg\to(\bar{c}q)^n c}|^2} \cdot \rho$
- $\overline{|\mathcal{M}_{qg\to(\bar{c}q)^n c}|^2} \Rightarrow$ explicit form of the matrix element squared available
- ρ can be interpreted as a probability to form real meson
  $\Rightarrow$ can be extracted from experimental data
  e.g. fixed-target LHCb data on $D/\bar{D}$ production asymmetry!

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





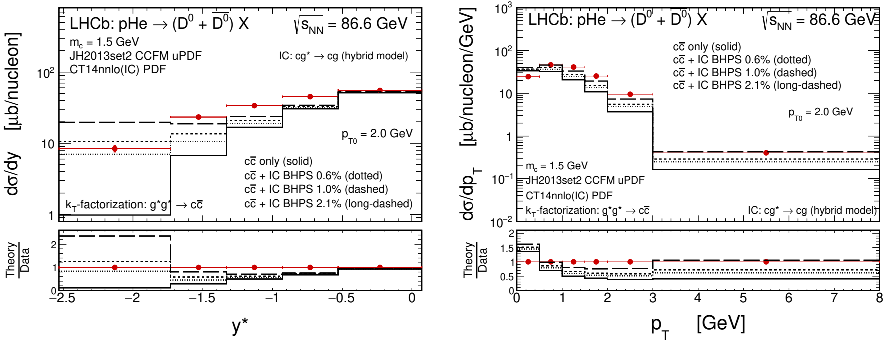


- both IC and recombination negligible at the LHCb in collider mode: $\sqrt{s} = 13$ TeV, $2 > y > 4.5$
- situation changes when approaching larger rapidities
- $y > 6$: IC dominates over the standard mechanism
- $y > 6$: recombination and the standard mechanism of similar size

Fixed-target charm data: Intrinsic Charm

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

- Fixed-target LHCb mode at $\sqrt{s} = 86.6$ GeV (D-meson production)

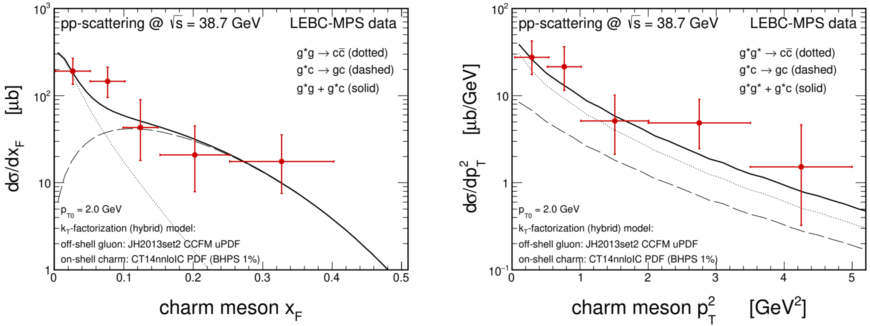


- some problems with understanding the LHCb fixed-target open charm data identified (R.M., Phys.Rev.D 102 (2020) 1, 014028)
- a new scenario proposed with the intrinsic charm contribution needed to describe the data points in the backward direction and at larger p_T's
- χ^2_{min}: $P_{ic} \sim 1.65\%$ but large uncertainties
  R.M, A. Szczurek, Phys.Rev.D 105 (2022) 014001

Fixed-target charm data: Intrinsic Charm

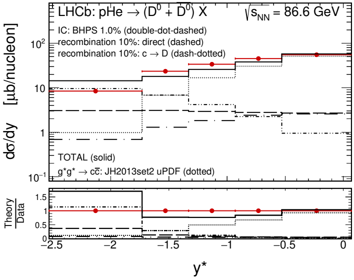
The fixed-target data on forward open charm meson production already exists:

- 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 component crucial for large-x_F data

Fixed-target charm data: Intrinsic Charm + Recombination

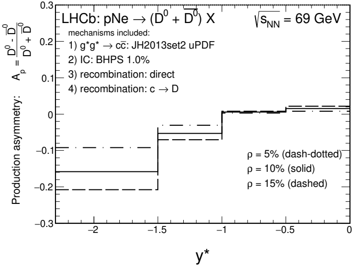


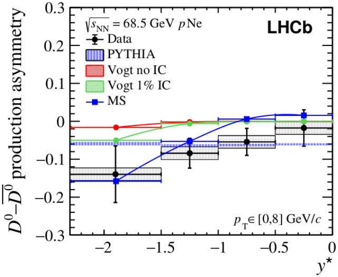
⇐ **the rapidity distribution for D^0-meson**:

- there is a room for the recombination mechanism with $\rho = 10\%$ together with the intrinsic charm contribution with $P_{IC} = 1.0\%$

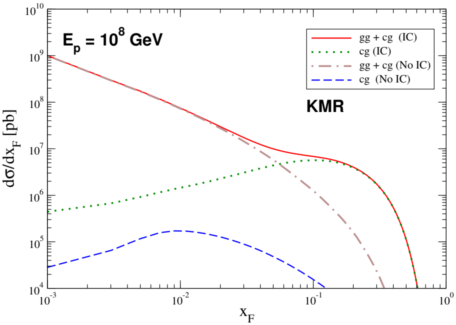
⇓ **very recent LHCb fixed-target data on the $D^0/\overline{D^0}$ production asymmetry**: arXiv:2211.11633 [hep-ph]

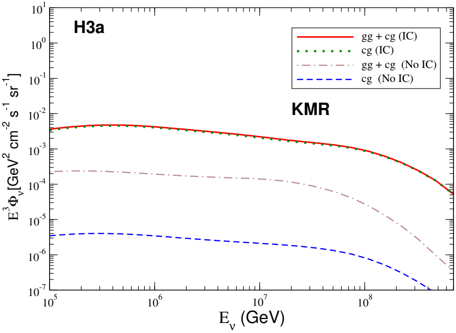
- our predictions consistent with the LHCb data taking $\rho = 10\%$!





IceCube: Prompt neutrino fluxes and intrinsic charm

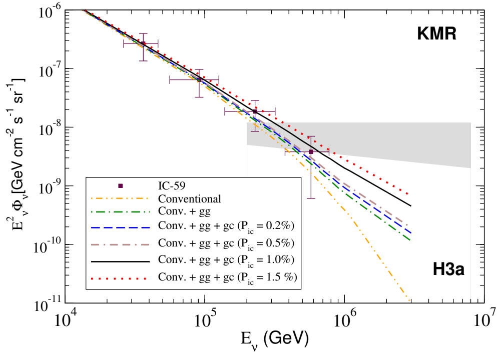




- intrinsic charm very important
- extrinsic charm negligible

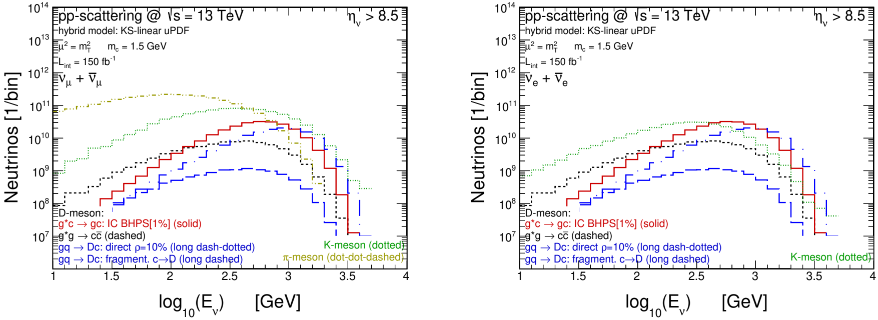
- the inclusion of the $cg^* \to cg$ mechanism driven by the intrinsic charm (IC) has a strong effect on the prompt neutrino flux
- the flux is enhanced by one order of magnitude when intrinsic charm is present ($P_{ic} = 1\%$ here)

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_ν, 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

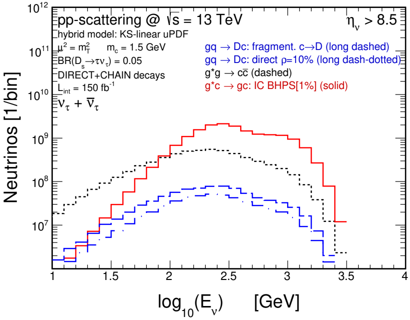
FASERν2: Far-forward neutrino fluxes



Semileptonic decays of $D^0, D^+, \Lambda_c \Rightarrow$ source of ν_e, ν_μ

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

FASERν2: Far-forward neutrino fluxes



D_s^+ meson decays $\Rightarrow$ dominant source of ν_τ

- direct $D_s^+ \to \tau^+ \nu_\tau$ and chain $D_s^+ \to \tau^+ \to \overline{\nu}_\tau$ decays
- no background from light mesons due to limited phase space for τ 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

Conclusions

We have shown that **the intrinsic charm** and **recombination** mechanisms can be extremely important for **far-forward charm production** at the LHC and beyond:

- D-meson at fixed-target LHCb experiments
  - a scenario proposed with the intrinsic charm contribution needed to describe the data points in the backward direction and at larger p_T's
  - extract the intrinsic charm probability P_{IC} ($\lesssim 1\%$)
  - still a room for recombination mechanism
  - the recombination probability from $D/\overline{D}$-production asymmetry ($\approx 10\%$)
- Prompt neutrino flux at IceCube Neutrino Observatory
  - upper limit on the intrinsic charm probability P_{IC} ($\lesssim 1\%$)
  - next step to include recombination
- Neutrino fluxes at Forward Physics Facilities (FPF) at the LHC (FASERν2,FLArE)
  - both IC and recombination important
  - ν_e, ν_μ fluxes difficult because of large backgrounds from light mesons
  - ν_τ flux at high energies dominated by intrinsic charm (recombination suppressed)therefore optimal to pin down the IC contribution in the nucleon

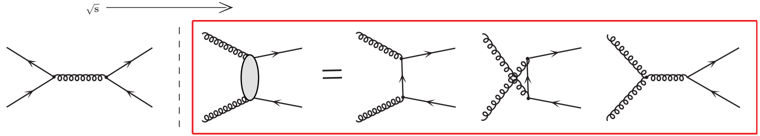
Thank You!

Backup Slides

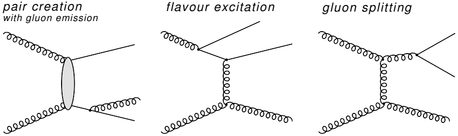
Charm cross section in QCD

The basic ingredient for the prompt neutrino flux ⇒ **pQCD charm quark production**

- the leading-order (LO) partonic processes for $Q\overline{Q}$ production ⇒ $q\bar{q}$-annihilation and gluon-gluon fusion (dominant at high energies)



- main classes of the next-to-leading order (NLO) diagrams:



the NLO and the NNLO corrections of a special importance for charm p_T-differential cross section!

collinear approach:

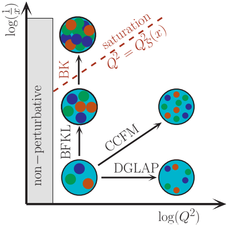
- state of the art for single particle spectra at NLO (FONLL, GM-VFNS)
- MC@NLO+PS for correlations
- NNLO not available for charm/bottom

k_T-factorizaton (high-energy factorization):

- exact kinematics from the very beginning
- correlation observables directly calculable
- some contributions even beyond the NLO available (also differentially)

prompt neutrino flux ⇒ high energy limit and far-forward charm production

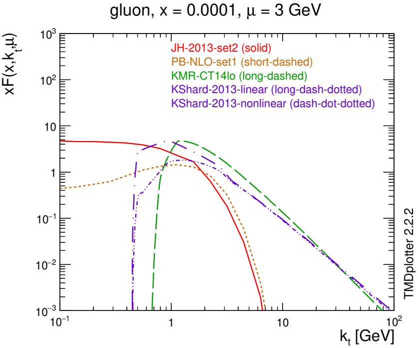
Unintegrated parton distribution functions (uPDFs)



Transverse momentum dependent PDFs: $\mathcal{F}_g(x, k_t^2, \mu)$

- CCFM evolution: Jung-Hautmann (JH2013)
- Parton Branching + DGLAP: Bermudez Martinez-Connor-Jung-Lelek-Zlebcik
- linear/nonlinear BK (saturation): Kutak-Sapeta (KS)
- modified DGLAP-BFKL: Kimber-Martin-Ryskin-Watt (KMR, MRW)
- modified BFKL-DGLAP: Kwieciński-Martin-Staśto (KMS)

- hard emissions from the uPDF ⇒ resummation of higher-order corrections
- k_T-fact. $g^* g^* \to c\bar{c}$ + KMR uPDF works very well for inclusive open charm and bottom mesons at th LHC (as well as for correlation observables)
- saturation effects possible to be studied within the KS uPDF
- open charm at the LHC: small-x and small/intermediate scales



The quark to meson transition

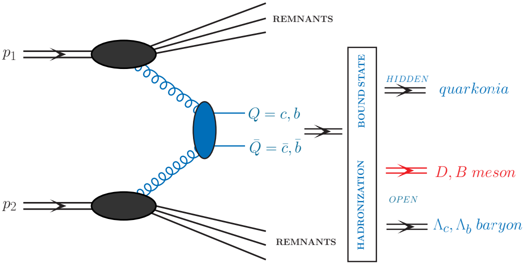
Heavy quark to open heavy meson fragmentation: $c \to D$ and $\bar{c} \to \overline{D}$

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:

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

- where $x_F^c = x_F/z$ and $D_{c \to D}(z)$ 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

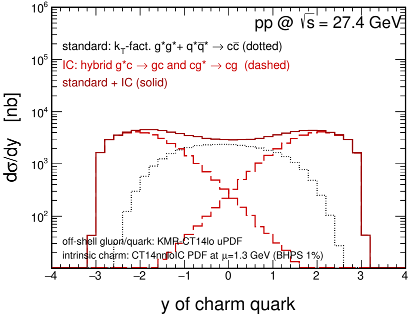


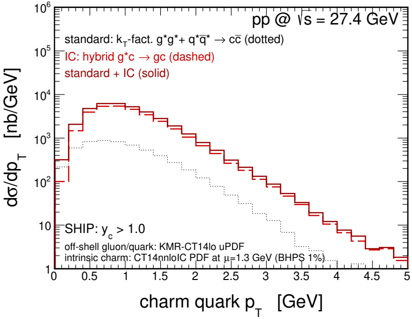
- $c \to D$: Peterson(z), $\varepsilon = 0.05$ (well known from e^+e^- data)
- $\eta_D = \eta_c$, $x_F = z \cdot x_F^c$, $z \in (0,1)$
- fragmentation fractions well known (Particle Data Group)

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:
(R.M, A. Szczurek, JHEP 10 (2020) 135)

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



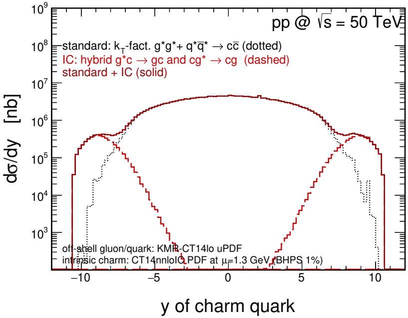


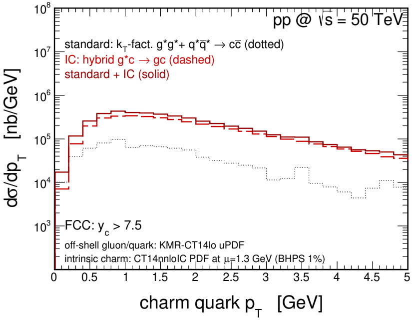
- at the lower energy ⇒ the intrinsic charm important in the whole rapidity spectrum
- transverse momentum distribution visibly enhanced

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:
(R.M, A. Szczurek, JHEP 10 (2020) 135)

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



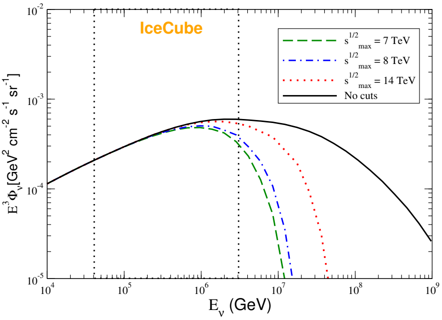


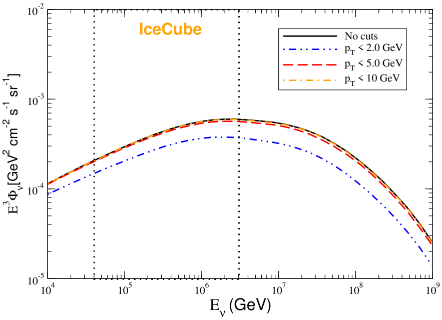
- the intrinsic charm important at $|y| > 7$
- transverse momentum distribution visibly enhanced

Kinematics probed with the IceCube prompt neutrino flux

Mapping the dominant regions of the phase space associated with $c\bar{c}$-pair production relevant for the **prompt flux at IceCube**

(V.P. Goncalves, R.M., R. Pasechnik, A. Szczurek, Phys.Rev.D 96 (2017) 9, 094026)





- recent: up to $E_\nu = 3 \cdot 10^6$ GeV $\Rightarrow$ **the LHC energy range**
- future: $E_\nu > 10^7$ GeV $\Rightarrow$ energy range beyond that probed in the LHC Run2
- flux sensitive to the $p_T < 5$ GeV

Kinematics probed with the IceCube prompt neutrino flux

Mapping the dominant regions of the phase space associated with $c\bar{c}$-pair production relevant for the **prompt flux at IceCube**

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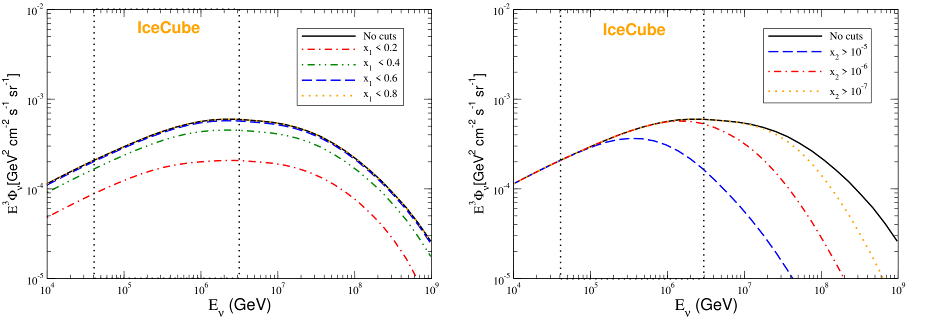
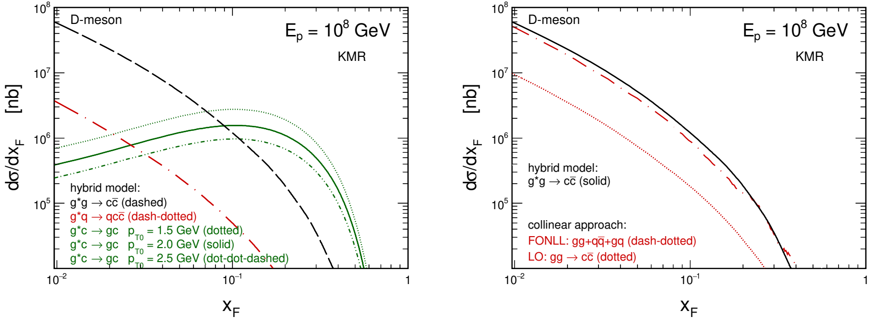


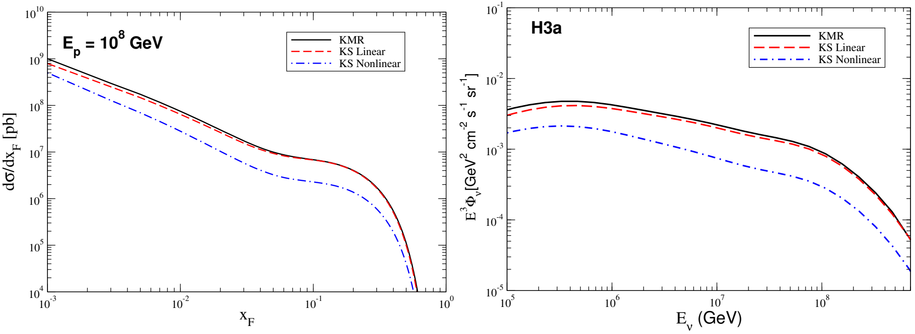
- projectile: $0.2 < x_1 < 0.6$
- target: $10^{-6} < x_2 < 10^{-5}$ (IceCube recently) and even $10^{-8} < x_2 < 10^{-5}$ (future)
- **far-forward production beyond the LHC range** $\Rightarrow$ very asymmetric kinematics

Predictions of our model for charm x_F-distributions



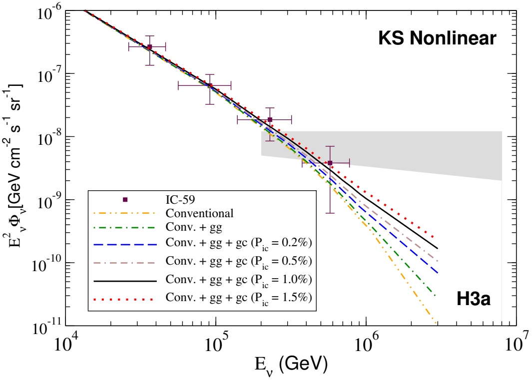
- when intrinsic charm is included the behavior of the x_F-distribution is strongly modified in the $0.03 \leq x_F \leq 0.6$ range
- the Feynman x_F-distribution for large x_F is dominated by the $cg^* \to cg$ mechanism with intrinsic charm
- our predictions for the standard charm production mechanism obtained with the hybrid model are consistent with the NLO collinear calculations by FONLL

Prompt neutrino fluxes and saturation effects



- sum of both production mechanisms: gg^*-fusion and the cg^* with IC BHPS 1%
- the KMR and KS linear predictions are similar
  $\Rightarrow$ BFKL effects not important for IceCube (which probes $0.2 < x_F < 0.5$)
- the KS nonlinear is a factor ≈ 3 smaller for $x_F = 0.2$
  $\Rightarrow$ saturation effects strongly modifies the magnitude of the distribution

Predictions and IceCube limits including saturation



- within the saturation scenario the impact of the prompt flux driven by the gluon-gluon fusion mechanism is even smaller and becomes negligible
- nonlinear QCD dynamics $\Rightarrow P_{ic} \leq 2.0\%$
- slightly higher than the central CT14nnloIC PDF set