Charm@FAIR

Antoni Szczurek
Institute of Nuclear Physics PAN, Kraków, Poland and Rzeszow University

in collaboration with R. Maciula, A. Cisek and I. Babiarz

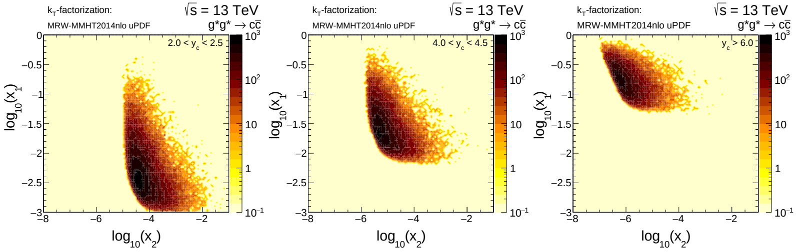
based on:
Phys.Rev.D 102 (2020) 1, 014028; J. High Energy Phys. 10 (2020) 135
Phys.Rev.D 105 (2022) 1, 014001; Phys.Lett.B 835 (2022) 137530
Phys.Rev.D110 (2024) 074032.

QCD@FAIR

11-14 November 2024, GSI Darmstadt, Germany

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



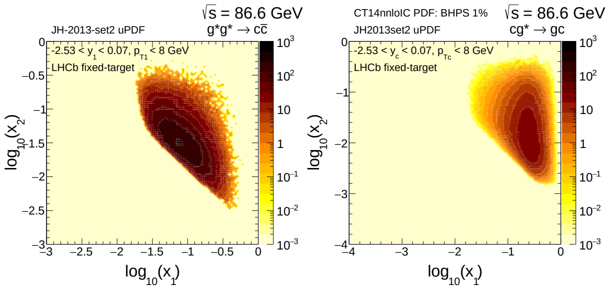
- gluon saturation, intrinsic charm content of the nucleon, recombination mechanism
- forward hadronization (e.g. color reconnection, beyond leading color strings, etc.)

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

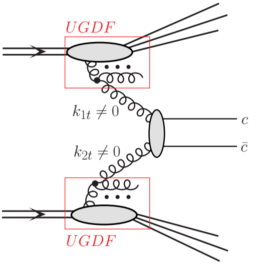


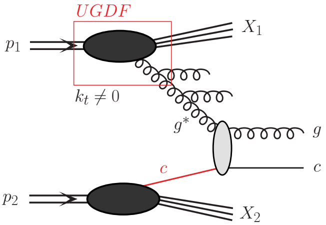
- ~~gluon saturation~~, intrinsic charm content of the nucleon, recombination mechanism
- forward hadronization (e.g. color reconnection, beyond leading color strings, etc.)

Experiments connected to forward charm production at lower energies:

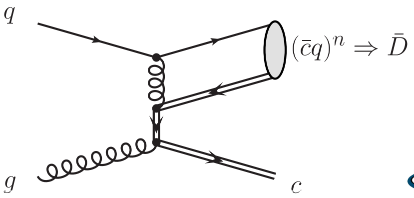
- fixed-target LHCb mode: D-meson, J/Ψ-meson at $\sqrt{s} = 86.6$ GeV and 68.5 GeV
- fixed-target SHIP experiment at SPS: ν_τ neutrino flux $\sqrt{s} = 27.4$ GeV
- fixed-target NA69/DsTau experiment at SPS: ν_τ neutrino flux $\sqrt{s} = 27.4$ GeV

QCD charm production mechanisms at forward directions

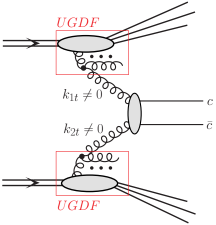




- $g^* g^* \rightarrow c\bar{c}$ ⇒ **the standard QCD mechanism** (and usually considered as a leading) of gluon-gluon fusion with off-shell initial state partons, calculated both in the full k_T-factorization approach and in the hybrid model
- $g^* c \rightarrow gc$ ⇒ the mechanism driven by **the intrinsic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

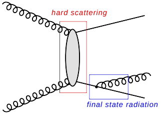
multi-differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{g^*g^* \to Q\bar{Q}}|^2}$$

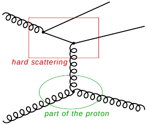
$$\times \quad \delta^2 \left(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t} \right) \mathcal{F}_g(x_1, k_{1,t}^2, \mu) \, \mathcal{F}_g(x_2, k_{2,t}^2, \mu)$$

- 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)

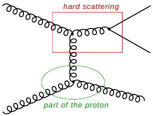
pair creation
with gluon emission



flavour excitation



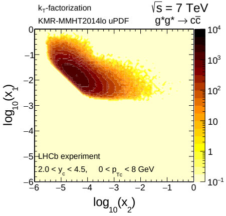
gluon splitting



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

Forward charm production at the LHCb in collider mode

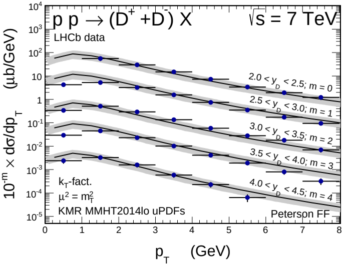
Open charm LHCb data in pp-scattering at $\sqrt{s}$ =7, 13 TeV:

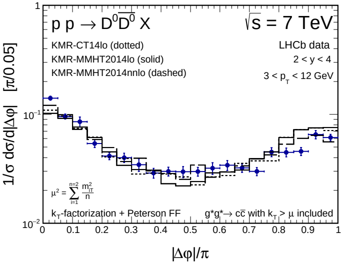


Detector acceptance: $2.0 < y < 4.5$ and $0 < p_T < 8$ GeV

- 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

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

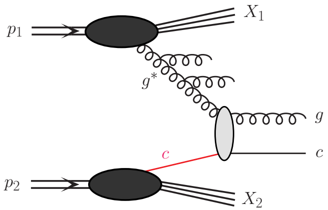




- k_T-factorization works very well

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 $\Rightarrow$

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

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

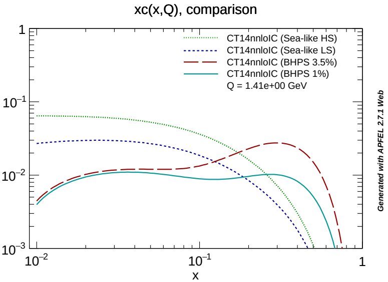
- $c(x_1,\mu^2) \Rightarrow$ collinear charm quark PDF (large-x)
- $\mathcal{F}_g(x_2,k_t^2,\mu^2) \Rightarrow$ off-shell gluon uPDF (small-x)

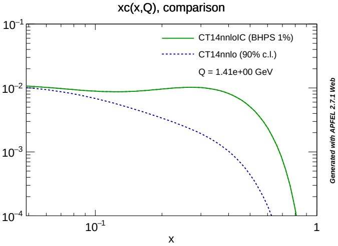
- $d\hat{\sigma}_{cg^*\to cg} \Rightarrow$ only in the massless limit (also available in KaTie)
- phenomenological regularization needed at $p_T \to 0 \Rightarrow$ we use PYTHIA prescription: $F_{sup}(p_T) = \frac{p_T^2}{p_{T0}^2+p_T^2}$, $\alpha_S(\mu_R^2 + p_{T0}^2)$, where $p_{T0} = 1.5$ GeV (free 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 $\Rightarrow$ multiple connections to the valence quarks of the proton

- dfferent pictures of non-perturbative $c\bar{c}$ content:
  - sea-like models
  - valence-like models
- we use the IC distributions from the CT14nnloIC and CT18FC PDFs
- Brodsky-Hoyer-Peterson-Sakai (BHPS) model
- Meson-Baryon Model (MBM)
- global experimental data put only loose constraints on the P_{ic} probability



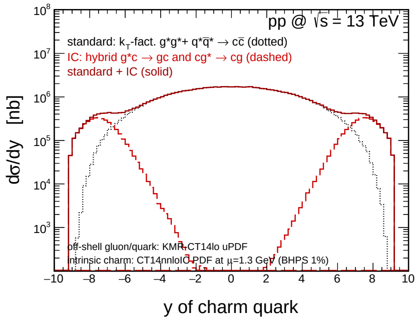


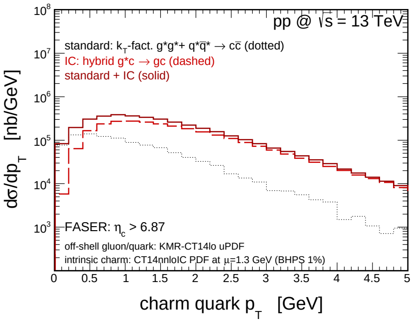
- the presence of an intrinsic component implies a large enhancement of the charm distribution at large x (>0.1) in comparison to the extrinsic charm prediction
- the models do not allow to predict precisely the absolute probability P_{ic}

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:

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



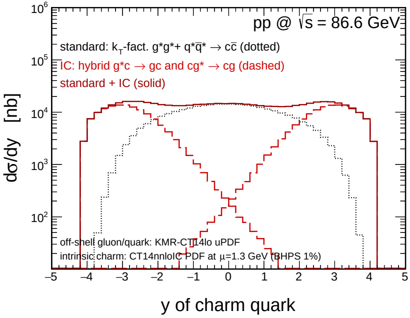


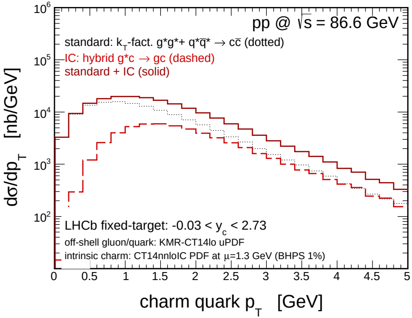
- the intrinsic charm important at $|y| > 6$
- transverse momentum distribution visibly enhanced

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:

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



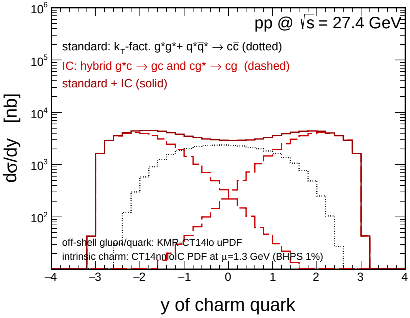


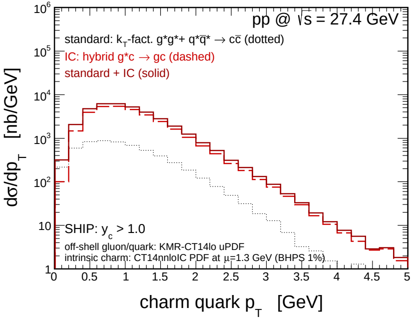
- at the lower energy $\Rightarrow$ the intrinsic charm important already at $|y| > 1$

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:

- SHIP/DsTau 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)



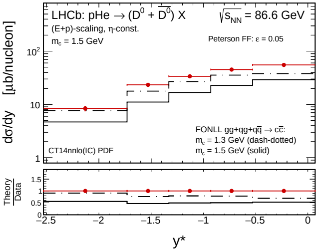


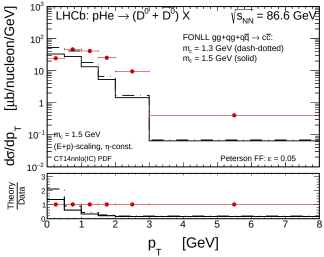
- at the lower energy $\Rightarrow$ the intrinsic charm important in the whole rapidity spectrum
- transverse momentum distribution visibly enhanced

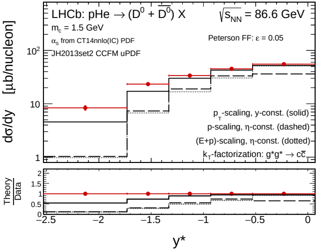
Fixed-target charm data at $\sqrt{s} = 86.6$ GeV: Intrinsic Charm

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)





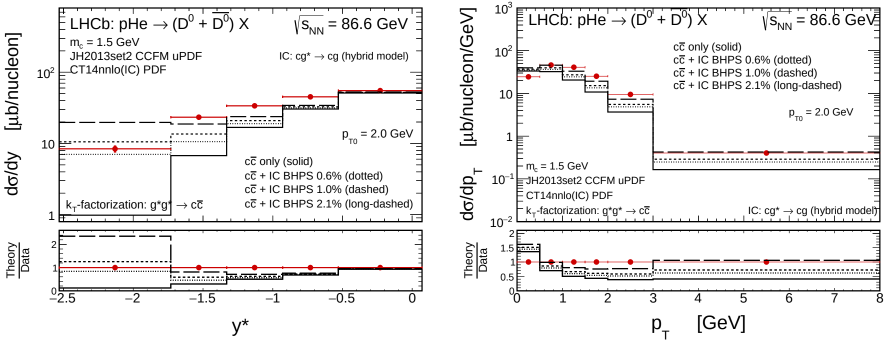


- some problems with understanding the LHCb fixed-target open charm data identified
- only upper limits of theoretical predictions (based on different approaches) can roughly describe the data
- different sources of uncertainties: charm quark mass, renormalization and factorization scales, details of the fragmentation procedure, etc.

Fixed-target charm data at $\sqrt{s} = 86.6$ GeV: 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)

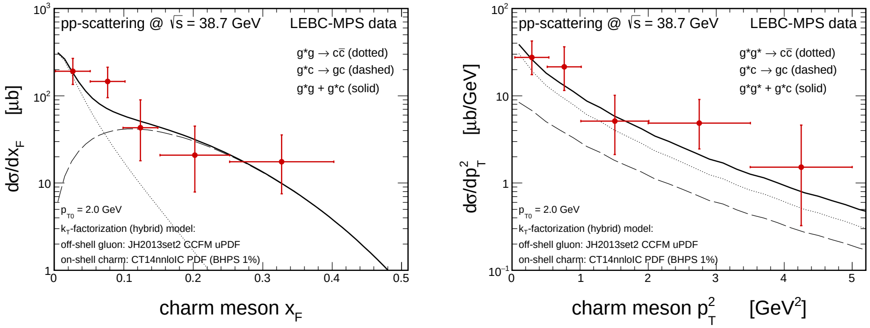


- some problems with understanding the LHCb fixed-target open charm data identified
- a new scenario proposed with the intrinsic charm contribution needed to describe the data points in the backward direction and at larger p_T's
- $\chi^2_{\min}$: $P_{ic} \sim 1.65\%$ but large uncertainties

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

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

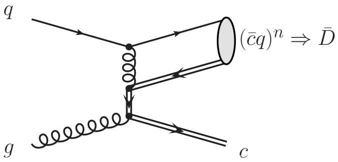
- Fermilab (1986): D-meson production in pp-scattering at $\sqrt{s} = 38.7$ GeV



- 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 component crucial for large-x_F data

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

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



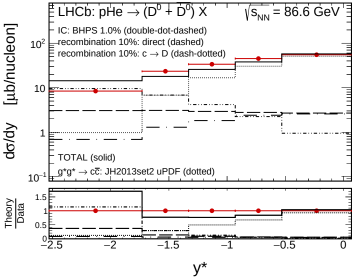
- short-distance process (in contrast with fragmentation)
- $(\bar{c}q)^n$: q has small momentum in the $\bar{c}$ rest frame
- q and $\bar{c}$ are in a state with definite color and angular momentum quantum numbers specified by n
- direct meson: $qg \to \bar{D}c$ and $\bar{q}g \to D\bar{c}$
- subsequent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

Fixed-target charm data at $\sqrt{s} = 86.6$ GeV: Recombination

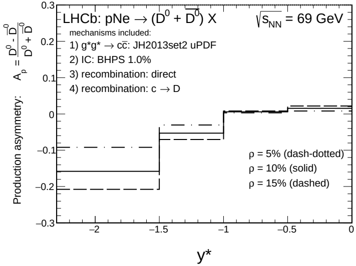


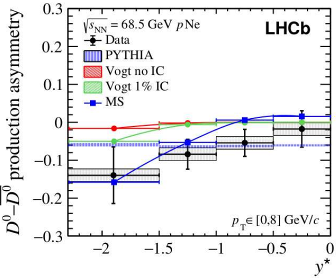
$\Leftarrow$ **the rapidity distribution for D^0-meson**:

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

$\Downarrow$ **very recent LHCb fixed-target data on the $D^0/\overline{D^0}$ production asymmetry** at $\sqrt{s} = 68.5$ GeV: Eur.Phys.J. C83 (2023) 541

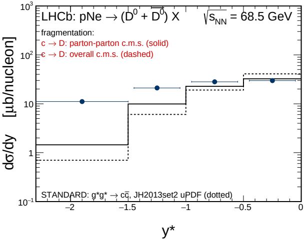
- our predictions consistent with the LHCb data taking $\rho = 10\%$!

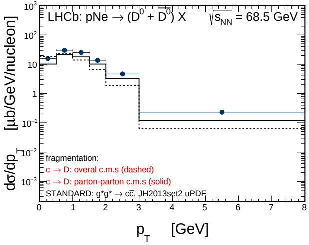




Fixed-target charm data at $\sqrt{s} = 68.5$ GeV: New analysis

- a lack of the well-established methods for the hadronization of heavy quarks into heavy hadrons in the forward/backward directions
- e.g. Pythia has only been tuned in the central region, and thus one should not expect reliable predictions in the forward direction
- dedicated forward physics tunes needed (some first attempts done only very recently in Phys.Rev.D 109 (2024) 1, 016010)

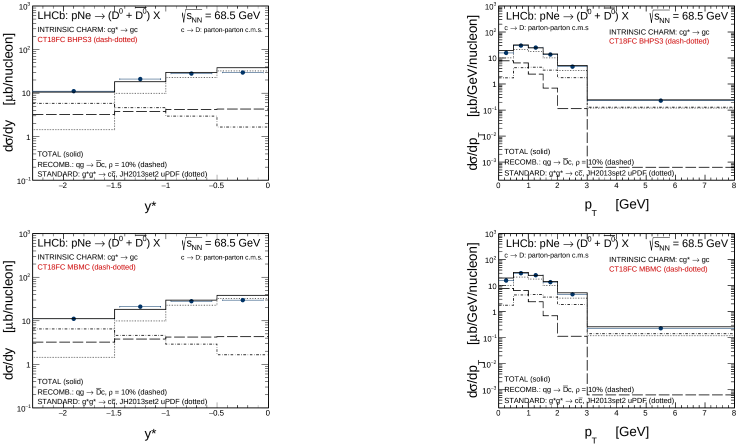




- the alternative and often used fragmentation procedure with fragmentation functions also has limitations when dealing with forward production and small transverse momenta
- our recent update with respect to the previous studies: the fragmentation procedure performed in the parton-parton c.m.s. (not in overall proton-proton c.m.s.)
- a visible sensitivity of the results to the details of the fragmentation procedure

Fixed-target charm data at $\sqrt{s} = 68.5$ GeV: CT18FC PDF

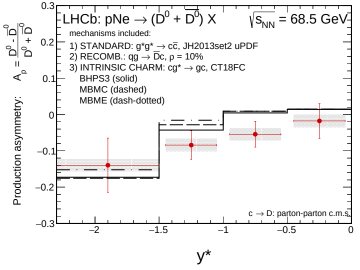
- CT18FC: BHPS and MBM

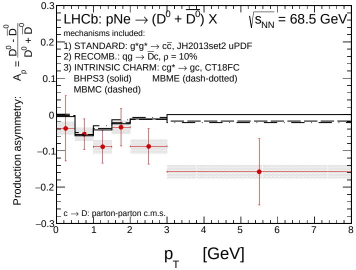


- both BHPS and MBM lead to very similar differential cross sections
- P_{IC}: CT18FC ($\approx 0.5\%$) and CT14nnloIC (between 1% and 2%)

Fixed-target charm data at $\sqrt{s} = 68.5$ GeV: The asymmetry

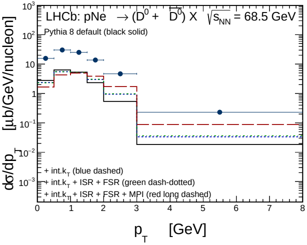
- BHPS3: symmetric $c = \bar{c}$
- MBMC/MBME: asymmetric $c \neq \bar{c}$ $\Rightarrow$ may lead to $D/\overline{D}$ production asymmetry





- backward rapidity region and small-p_T: the asymmetry well described by the recombination only (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 $D/\overline{D}$ asymmetry at large-p_T, however, the effect is to small to describe the data points

PYTHIA8 result

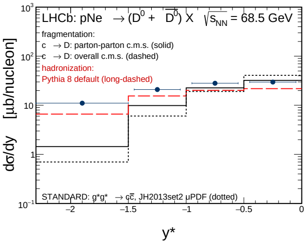


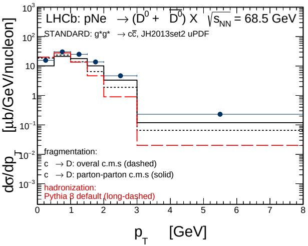
Rather small cross section

We start from hard processes with charm

What about other parton shower effects ?

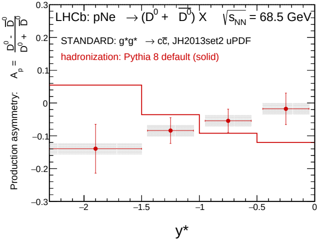
gg-fusion in k_t-factorization + PYTHIA8 hadronization

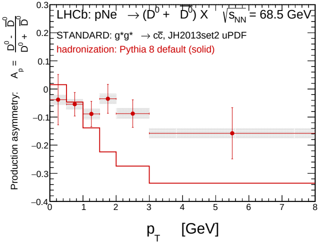




Much larger cross section

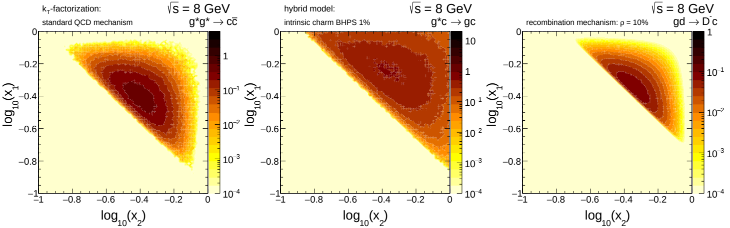
gg-fusion in k_t-factorization + PYTHIA hadronization





incorrect asymmetry !!!

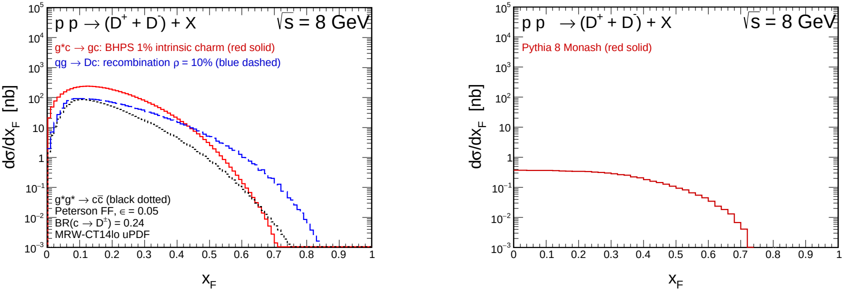
What if we go to even lower energies?



- 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^-; Λ/D enhancement; hadronization in central regions and in forward directions, etc.)
- SIS100 (CBM, NuStar) can contribute?

SIS100

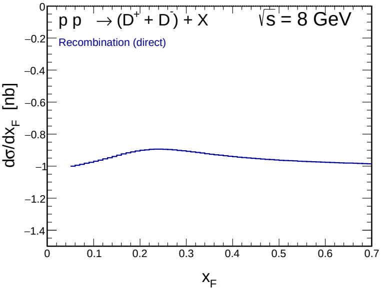
- different mechanisms and theoretical approaches.

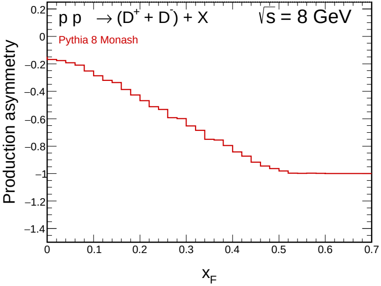


- conventional (gg fusion), recombination and IC of similar size
- Pythia result is very small !
- Therefore very interesting.

SIS100, asymmetry

- production asymmetry: $A = \frac{D^+ - D^-}{D^+ + D^-}$

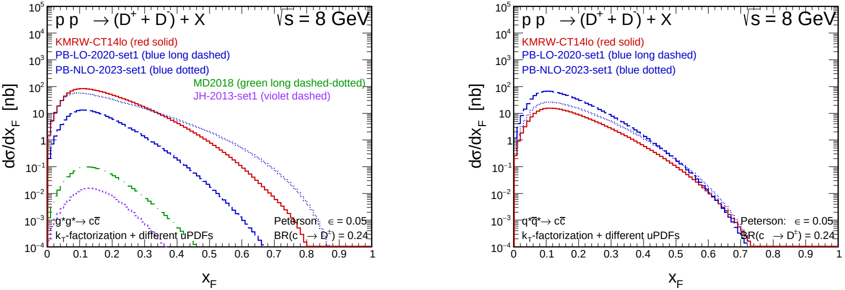




- the result from pure recombination must be supplemented by gg and $q\bar{q}$ mechanisms. Then the asymmetry will be smaller.

SIS100, k_t-factorization

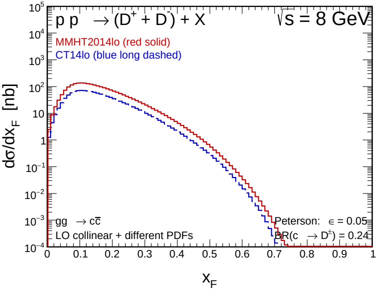
- k_T-factorization and different gluon and quark uPDFs

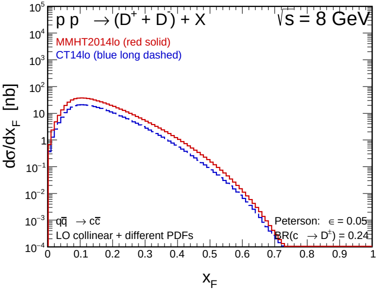


- gg and $q\bar{q}$ are comparable. It was not so at larger energies.

SIS100, collinear approach

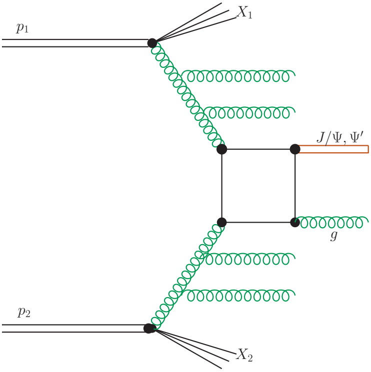
- LO collinear approach and different collinear PDFs

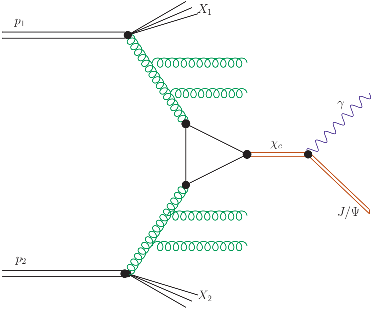




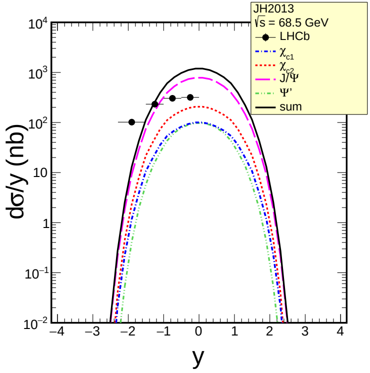
- There is some difference due to the choice of parton distributions.

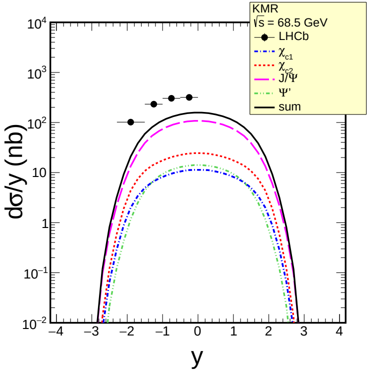
$pp \longrightarrow J/\psi$ (inclusive production)





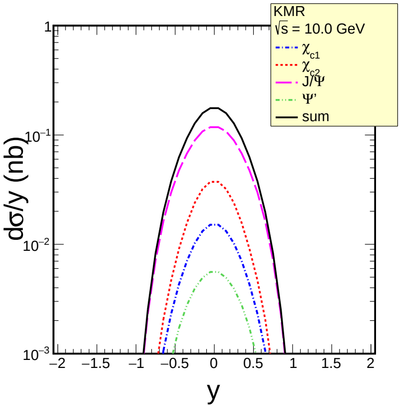
$pp \to J/\psi$ at $\sqrt{s} = 68.5$ GeV

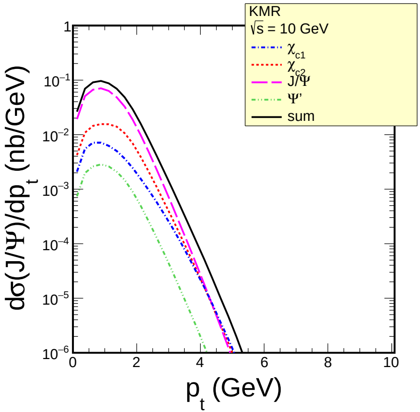




We get proper order of magnitude

$pp \to J/\psi$ (inclusive production) at $\sqrt{s} = 10$ GeV





Cross section seems OK

$pp \longrightarrow J/\psi$ (inclusive production)

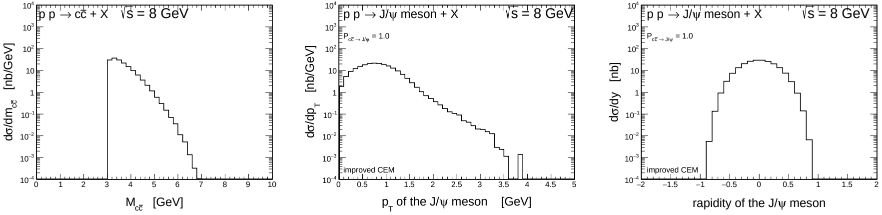


Figure: First results in the improved color evaporation model.
This numbers should be multiplied by 0.02

A fraction of nb. In addition it must be multiplied by 0.06 (J/ψ decay branching fraction).

$pp \to ppJ/\psi$ in k_t-factorization (exclusive production)

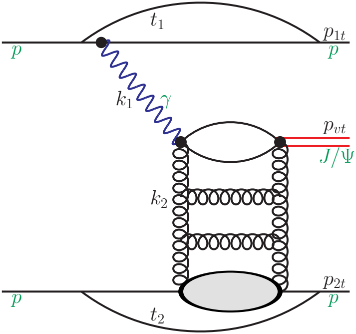


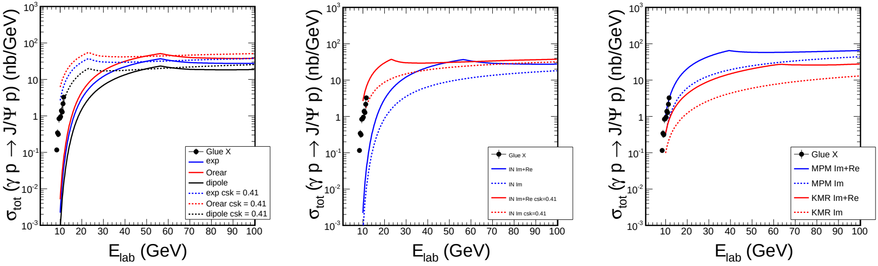
Figure: Two possible contributions.

Coherent sum of both processes

One has to understand first $\gamma p \to J/\psi p$.

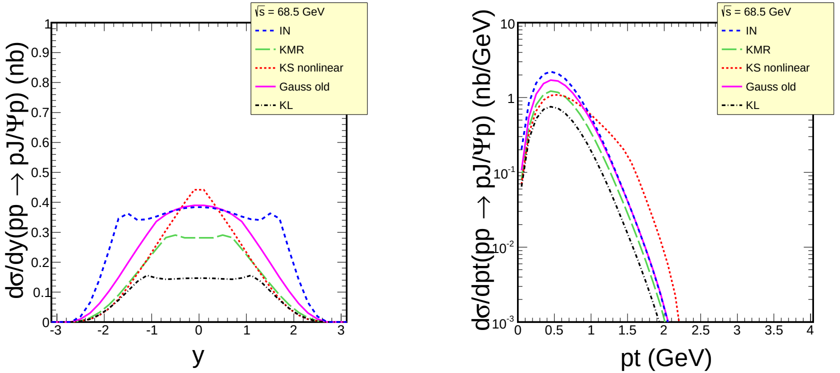
$\gamma p \to J/\psi p$, QCD approach

according to Cisek, Schäfer, Szczurek



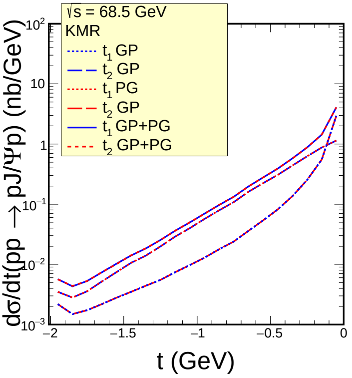
Imaginary part of the amplitude is almost sufficient at high energies. Impossible to describe the Glue-X data without real part of the amplitude.

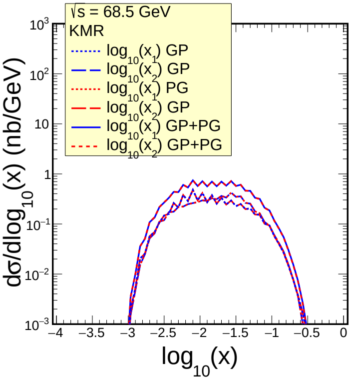
$pp \to ppJ/\psi$ at $\sqrt{s} = 68.5$ GeV



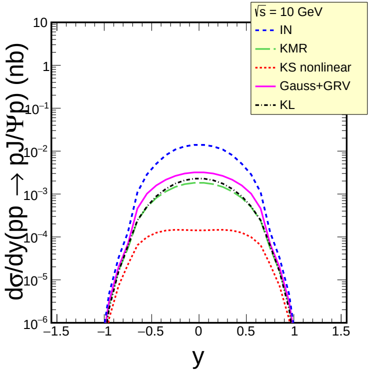
Was not measured at this energy

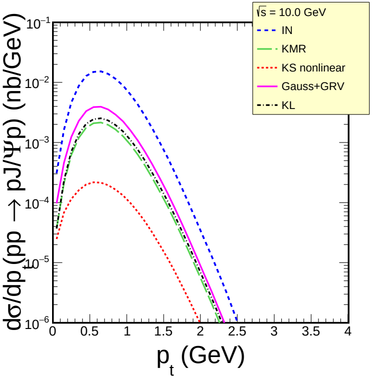
$pp \to ppJ/\psi$ at $\sqrt{s} = 68.5$ GeV





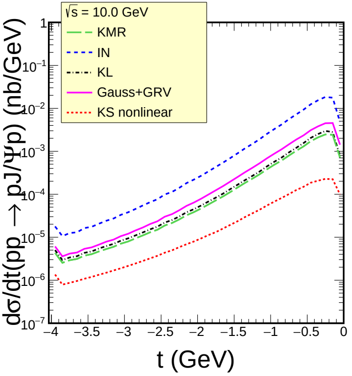
$pp \to ppJ/\psi$ at $\sqrt{s} = 10$ GeV

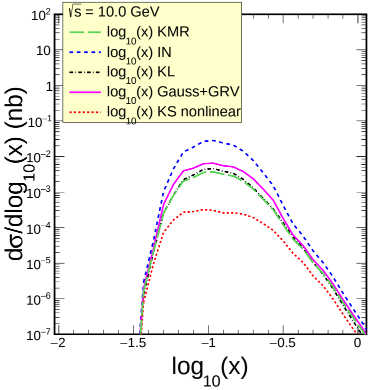




Can we assure exclusivity ?

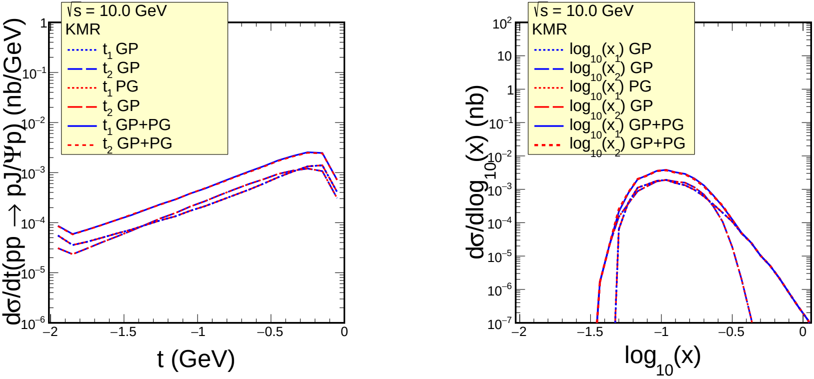
$pp \to ppJ/\psi$ at $\sqrt{s} = 10$ GeV





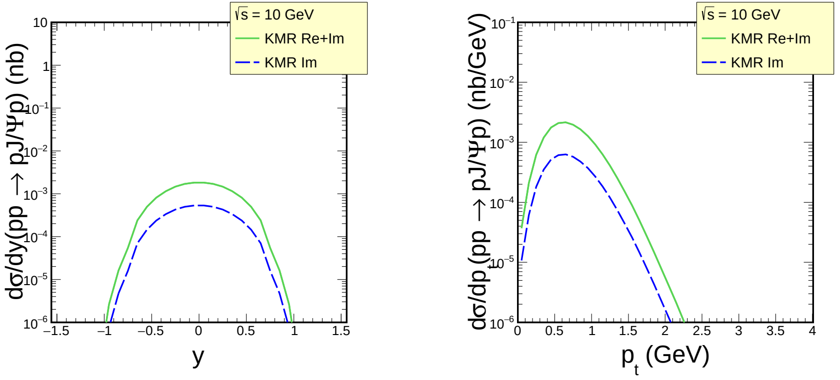
large-x, Work on UGDF may be required

$pp \to ppJ/\psi$ at $\sqrt{s} = 10$ GeV



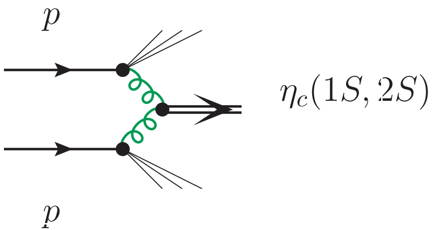
individual components (photon-pomeron, pomeron-foton)

$pp \to ppJ/\psi$ at $\sqrt{s} = 10$ GeV



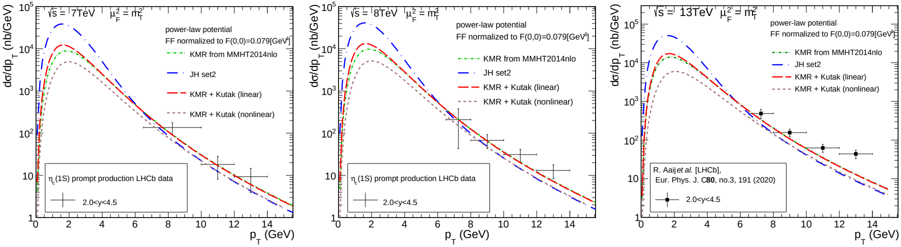
Real part is large and must be included !

$pp \longrightarrow \eta_c$ (inclusive cross section)



This was studied at the LHC by Babiarz, Schäfer and Szczurek, JHEP2002 (2020) 037.

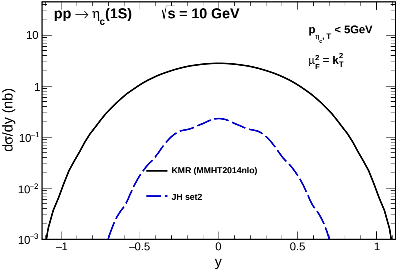
$pp \to \eta_c$ at the LHC

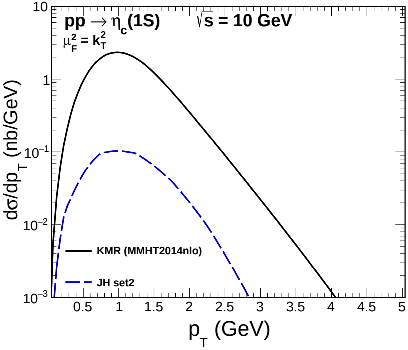


Quite good agreement

We can go to smaller energies.

$pp \to \eta_c$ at $\sqrt{s} = 10$ GeV





Big difference for different UGDFs

Rather small cross section and branching fractions are small.

decay channels: $p\bar{p}$, $\gamma\gamma$, $\eta\pi^+\pi^-$, $\phi\phi$, $\pi^+\pi^-\pi^+\pi^-$

Multiparton Fock components

Higher Fock components with charm:
$uudc\bar{c} + uudc\bar{c}u\bar{u} + uudc\bar{c}d\bar{d} + ...$
In the Brodsky et al. approach the probability distribution of a five particle IC Fock state in the nucleon

$$dP_{ic,5} = P_{ic}^{0} N_5 \int dx_1 ... dx_5 \int dk_{1,x} ... dk_{5,x} \int dk_{1,y} ... dk_{5,y}$$

$$\delta\left(1 - \sum_{i=1}^{5}\right) \delta\left(\sum_{i=1}^{5} k_{xi}\right) \delta\left(\sum_{i=1}^{5} k_{yi}\right) \frac{1}{\left(m_p^2 - \sum_{i=1}^{5} \frac{m_i^2}{x_i}\right)^2} . (1)$$

This is used by Ramona Vogt recently for J/ψ, D^0 and $\bar{D}^0$.

Multiparton Fock components

As an example minimal configuration is:
$uudc\bar{c}$ for D^0 (leading),
$uudc\bar{c}u\bar{u}$ for $\bar{D}^0$ (subleading).
Different minimal configuration for D^0 and $\bar{D}^0$.
This leads to $D^0 - \bar{D}^0$ and $D^+ - D^-$ asymmetry.
as in our recombination effect.
The probability of 5- and 7-parton state is not known.
The cross section is:

$$d\sigma_{ic} = dP_5 \sigma_{pp}^{tot} F_d \tag{2}$$

$$\sigma_{ic}^{D}(pp) = \sigma_{ic}(pp) \; , \tag{3}$$

$$\sigma_{ic}^{J/\psi}(pp) = F_c \sigma_{ic}(pp) \; . \tag{4}$$

Criticism: two unknown factors!

Conclusions

We have shown that **the intrinsic charm** and **the recombination** mechanisms can be extremely important for **forward charm production** at intermediate energies as well as close-to-threshold energies:

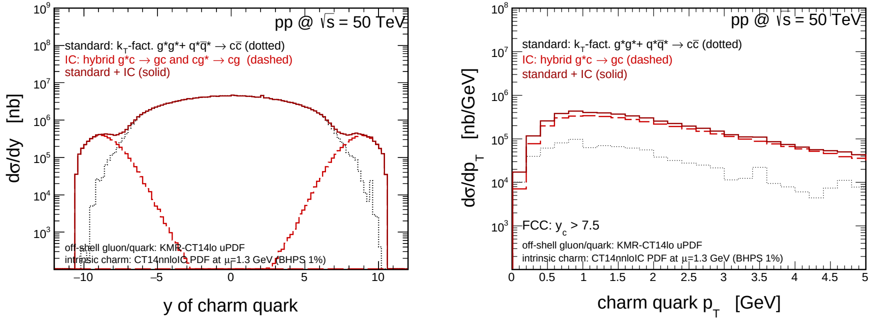
- D-meson at fixed-target LHCb experiments
  - a scenario proposed with the intrinsic charm contribution needed to describe the data points in the backward direction and at larger p_T's at the LHC fixed target experiments.
  - upper limit for the intrinsic charm probability P_{IC} ($\approx 0.5\%$) with the CT18FC
  - still a room for recombination mechanism
  - the recombination probability from $D/\overline{D}$-production asymmetry ($\approx 10\%$)
  - the $D/\bar{D}$ production asymmetry in the backward region and at small transverse momenta well explained by the recombination mechanism at FOG device.
  - the asymmetry at larger transverse momenta can be described neither by the recombination mechanism nor by the asymmetric intrinsic charm
  - Inclusive cross section for J/ψ production is rather small and strongly depends on UGDFs used.
  - Exclusive cross section for J/ψ production is even smaller. Can we guarantee rapidity gaps (exclusivity) ?
  - Inclusive cross section for η_c not too small but branching fractions are very small. Different decay channels must be studied.

Backup Slides

Intrinsic charm at the LHC and beyond

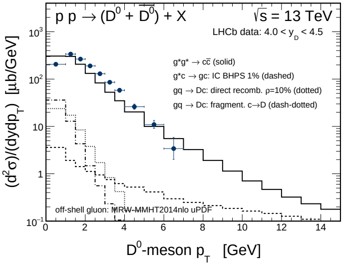
A possible impact of the intrinsic charm component on the forward charm particle production in already existing or future experiments at different energies:

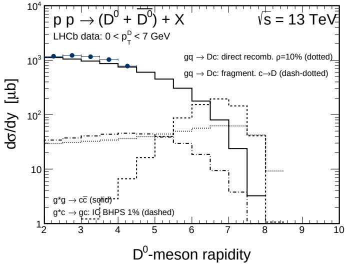
- Future Circular Collider (FCC) (D-meson production)

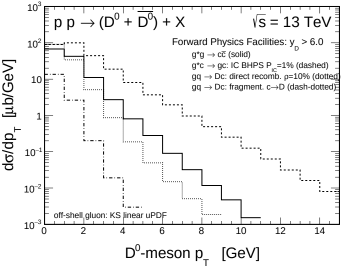


- the intrinsic charm important at $|y| > 7$
- transverse momentum distribution visibly enhanced

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





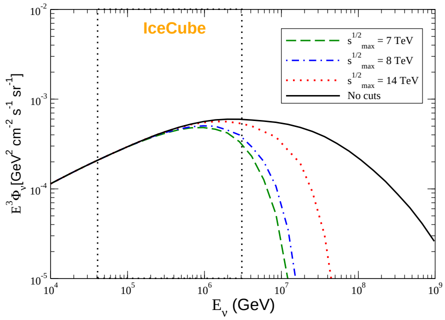


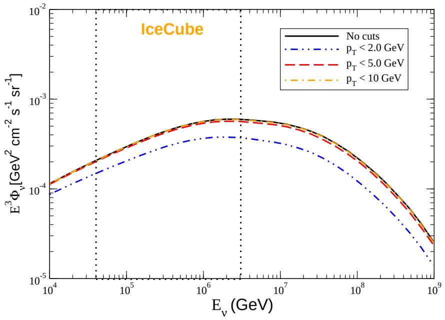
- both IC and recombination negligible at the LHCb in collider mode: $\sqrt{s} = 13$ TeV, $2 > y > 4.5$
- situation changes when approaching larger rapidities
- $y > 6$: IC dominates over the standard mechanism
- $y > 6$: recombination and the standard mechanism of similar size

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)



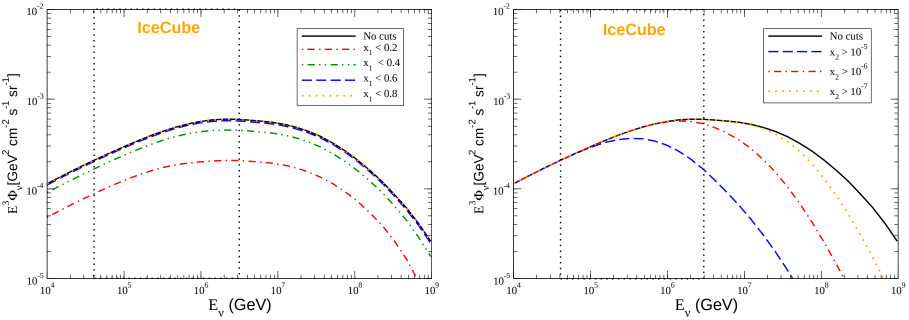


- recent: up to $E_\nu = 3 \cdot 10^6$ GeV $\Rightarrow$ **the LHC energy range**
- future: $E_\nu > 10^7$ GeV $\Rightarrow$ energy range beyond that probed in the LHC Run2
- flux sensitive to the $p_T < 5$ GeV

Kinematics probed with the IceCube prompt neutrino flux

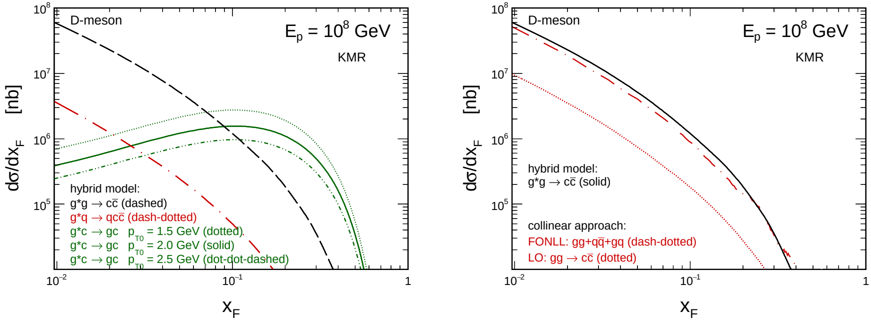
Mapping the dominant regions of the phase space associated with $c\bar{c}$-pair production relevant for the **prompt flux at IceCube**

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



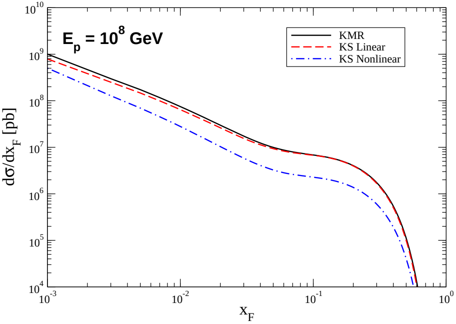
- projectile: $0.2 < x_1 < 0.6$
- target: $10^{-6} < x_2 < 10^{-5}$ (IceCube recently) and even $10^{-8} < x_2 < 10^{-5}$ (future)
- **far-forward production beyond the LHC range** ⇒ very asymmetric kinematics

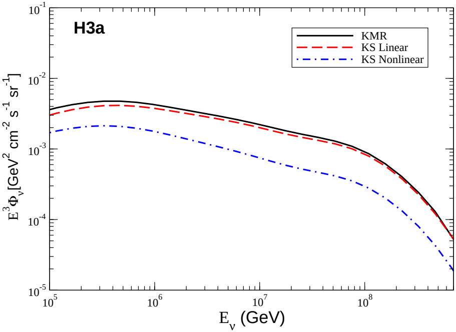
Predictions of our model for charm x_F-distributions



- 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

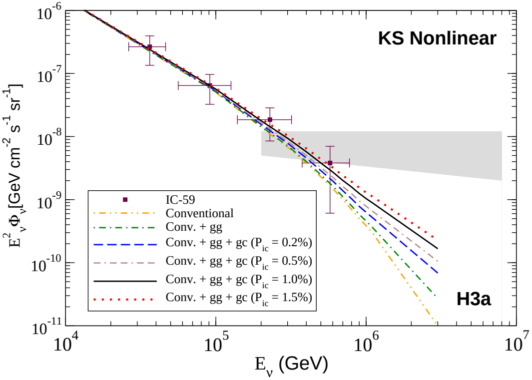
Prompt neutrino fluxes and saturation effects





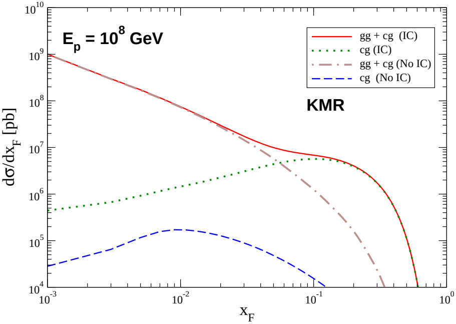
- sum of both production mechanisms: gg^*-fusion and the cg^* with IC BHPS 1%
- the KMR and KS linear predictions are similar
  $\Rightarrow$ BFKL effects not important for IceCube (which probes $0.2 < x_F < 0.5$)
- the KS nonlinear is a factor ≈ 3 smaller for $x_F = 0.2$
  $\Rightarrow$ saturation effects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

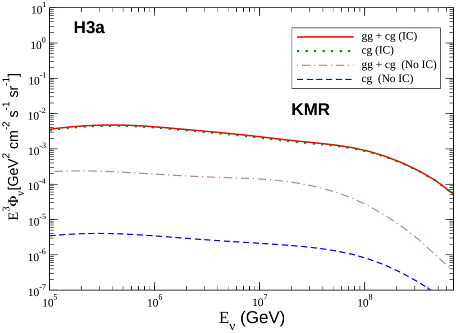
Predictions and IceCube limits including saturation



- 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

IceCube: Prompt neutrino fluxes and intrinsic charm

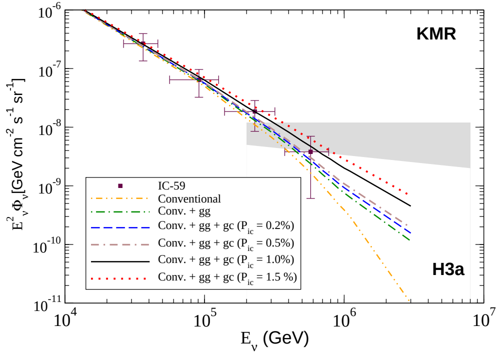




- intrinsic charm very important
- extrinsic charm negligible

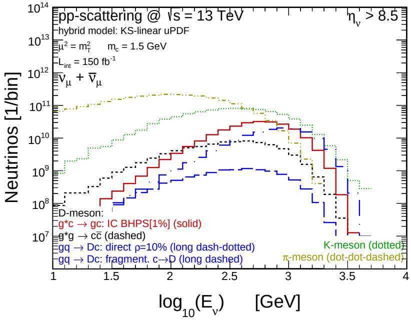
- the inclusion of the $cg^* \to cg$ mechanism driven by the intrinsic charm (IC) has a strong effect on the prompt neutrino flux
- the flux is enhanced by one order of magnitude when intrinsic charm is present ($P_{ic} = 1\%$ here)

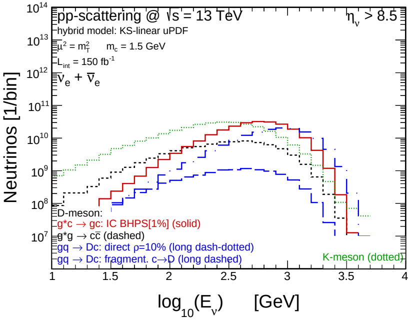
IceCube: Predictions and limits for intrinsic charm



- 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

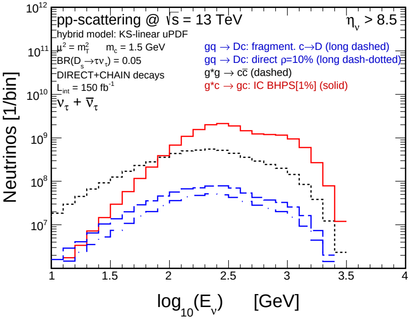




Semileptonic decays of $D^0, D^+, \Lambda_c \Rightarrow$ source of ν_e, ν_μ

- $E_\nu > 100$ 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