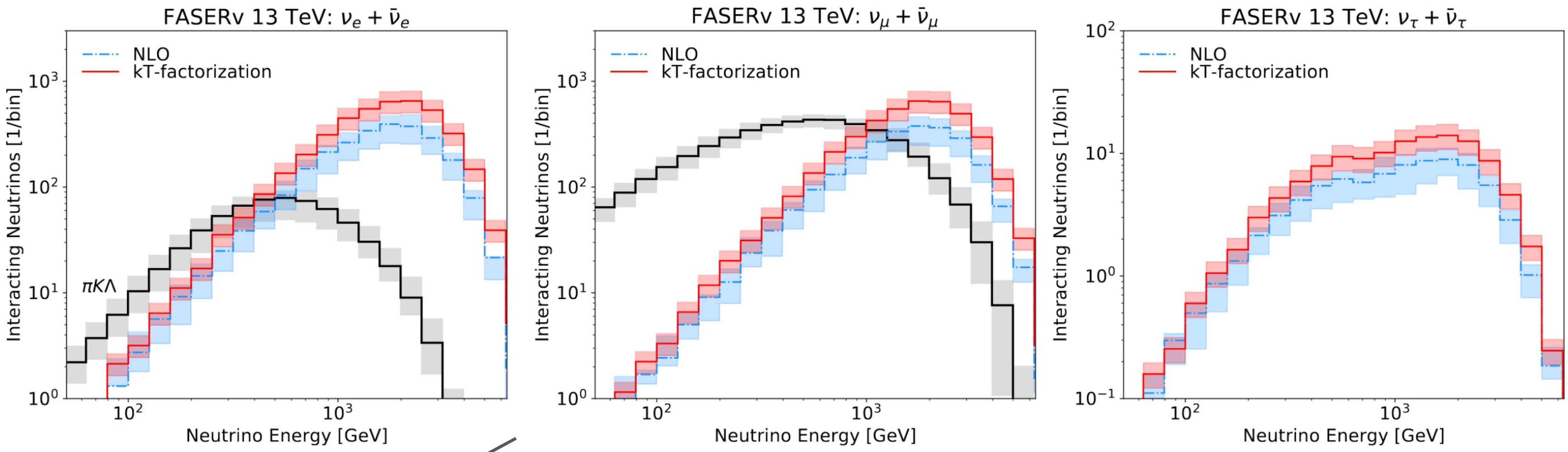
Forward Neutrinos from Charm at Large Hadron Collider



arXiv:2306.01578

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- ✔ Different QCD schemes for $c\bar{c}$ production
- ✔ Fragmentation schemes for $c\bar{c} \rightarrow$ mesons
- ✔ Fitting to 13 TeV data from LHCb and neutrino fluxes

QCD schemes: $pp \to c\bar{c}$

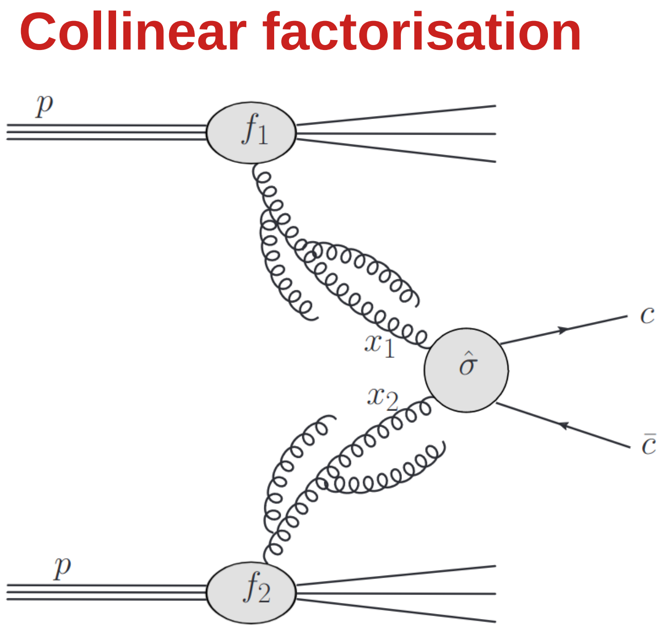

FIG. 1. Left: gluon-gluon fusion process for charm production in hadron-hadron collisions in the collinear factorization approach. f_1, f_2 are the integrated gluon distribution functions which depend on the longitudinal momentum fractions x_1, x_2 and the hard scale of the partonic sub-process. Right: the same process, illustrated for the case of forward production in the k_T-factorization. The gluon x_1 is treated on-shell, and the gluon x_2 is off-shell with transverse momentum k_T. $\hat{\sigma}$ is the partonic cross section which is on-shell (left panel) and takes into account off-shellness of one gluon (right panel).

QCD schemes:

$$pp \to c\bar{c}$$

Collinear factorisation

$$\frac{d^2\sigma_{pp}}{dy\,dp_T^2}(s, m_c^2) = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_i(x_1, \mu_F^2)\, f_j(x_2, \mu_F^2)\, \frac{d^2\widehat{\sigma}_{ij}}{dy\,dp_T^2}(\hat{s}, m_c^2, \mu_F^2, \mu_R^2)$$

CT14nlo central

NLO

Scales
μ_F: factorisation
μ_R: renormalisation

m_c = 1.3 GeV
$\sqrt{s}$ = 13 TeV

k_T factorisation

$$\sigma_{pp}(s, m_c^2) = \int dx_1\, dx_2\, \frac{d^2\mathbf{k}_T}{\pi}\, f(x_1, \mu^2)\, \mathcal{F}(x_2, \mathbf{k}_T)\, \widehat{\sigma}^{\text{on-off}}(\hat{s}, \mathbf{k}_T, m_c)$$

Un-integrated
k_T-dependent PDF

g_1 on-shell

g_2 off-shell

$\hat{\sigma}^{\text{on-off}}$ is LO
$\Rightarrow$ Introduce k-factor

Fragmentation
$c\bar{c} \rightarrow D$-Mesons

- ✘ Typical fragmentation functions determined from LEP data
- ✘ Not especially tailored to high rapidity and low p_T calculations needed for FPF
- ✘ Ignores hadronisation involving beam remnants
- ✘ Pion fixed target experiments: WA82, E769, E791
  - ➔ Hadron momentum spectrum as hard as or even harder than the charm quark spectra

$D_H(z)$ ≡ Charm energy fraction converted to hadron energy
$z = p_H/p_c$

Pythia-inspired fragmentation

MC generators typically use more sophisticated hadronisation schemes. In particular, `Pythia` uses the Lund string model in which coloured objects are connected by a colour string containing the field lines of the strong force. This model can intuitively explain, for example, how a charm quark connected to a beam remnant valence quark will be pulled forward, potentially gaining energy.

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Pythia-inspired fragmentation

Charm production using Pythia produces a sampling of events, with each event characterized by the parton momentum $\boldsymbol{p}_c$, the hadron momentum $\boldsymbol{p}_H$, a hadron ID and an event weight w. The events in the sample follow a distribution $d^2\sigma_c^{P8}$ for the charm quarks and $d^2\sigma_H^{P8}$ for the charm hadrons. Re-weighting procedure: adjust weights

$$w \rightarrow w \times \frac{d^2\sigma_c/(dp_{T,c}dy_c)}{d^2\sigma_c^{P8}/(dp_{T,c}dy_c)}$$

Determining parameters
Fitting $d^2\sigma$ to LHC data

- $D^0/\overline{D}^0$, $D^\pm$, D_s data at 13 TeV from LHCb for reference
- Vary parameters pertinent to QCD scheme and compare against data
- Define χ^2 normalised to number of p_T bins
  - For forward predictions, important to ensure that fitting is not skewed by the availability of significantly more data at lower rapidities $2 \leq y \leq 3$ rather at, say, $y \geq 4$
- Determine χ^2/d.o.f for each set of parameters
- Obtain best-fit parameter set that minimises χ^2/d.o.f, and parameter uncertainties

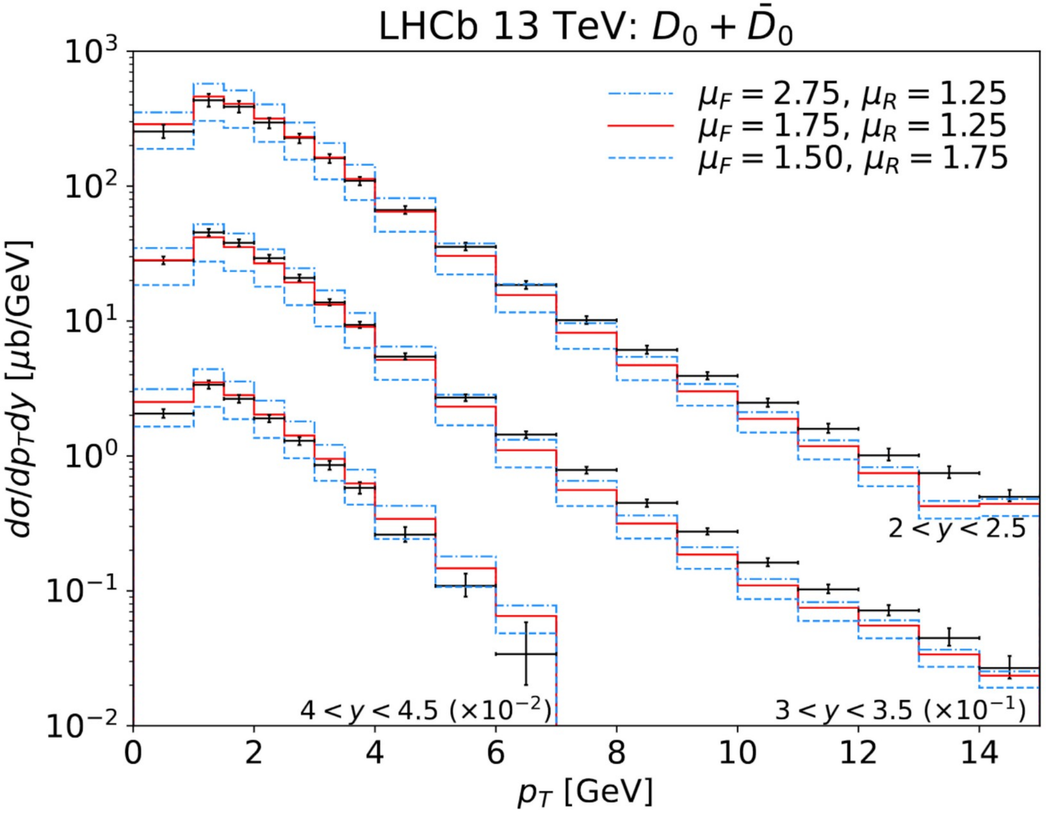
Collinear factorisation

Determining parameters

Fitting $d^2\sigma$ to LHC data

- Scales $\{\mu_F, \mu_R\}$ as parameters
- *Introduce* Gaussian smearing on charm p_T
  - Inspired by Bai et al[†], but modified to maintain energy conservation
  - Needed to match p_T-shape of computed $d^2\sigma$ vis-à-vis LHCb data
  - Finally, $\langle k_T \rangle = 1.5$ GeV

[†]arXiv:2002.03012



Collinear factorisation

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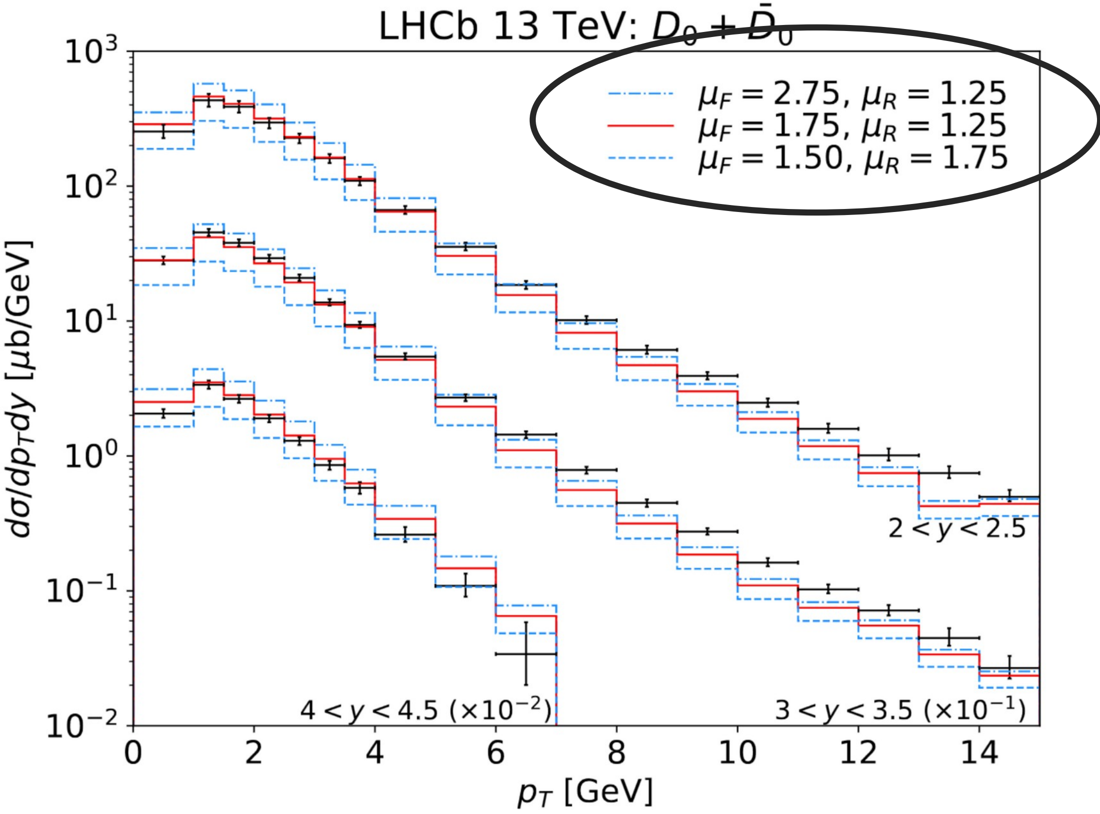
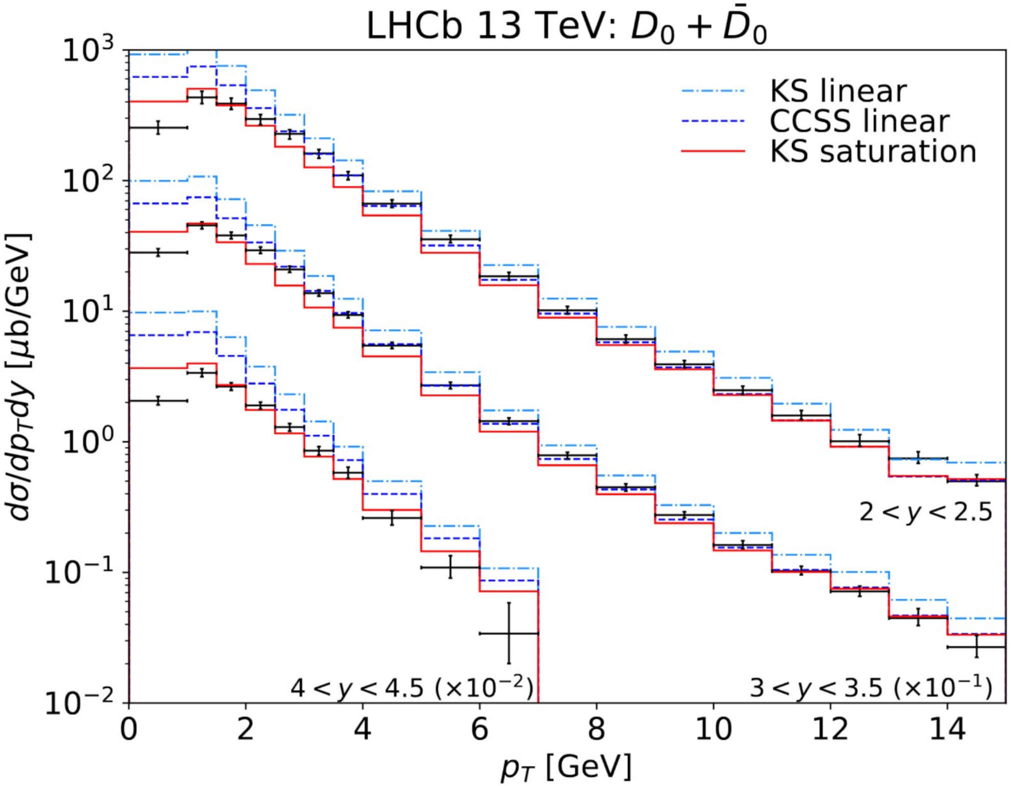


Determining parameters

Fitting $d^2\sigma$ to LHC data

- Different choices for $\mathcal{F}(x_2, \boldsymbol{k}_T)$
  - Kutak-Sapeta (KS)† with non-linear evolution (saturation)
  - KS linear (w/o saturation)
  - Ciafaloni-Colferai-Salam-Stasto (CCSS) linear‡
- Fit parameter: $k = 2.32 \pm 0.54$

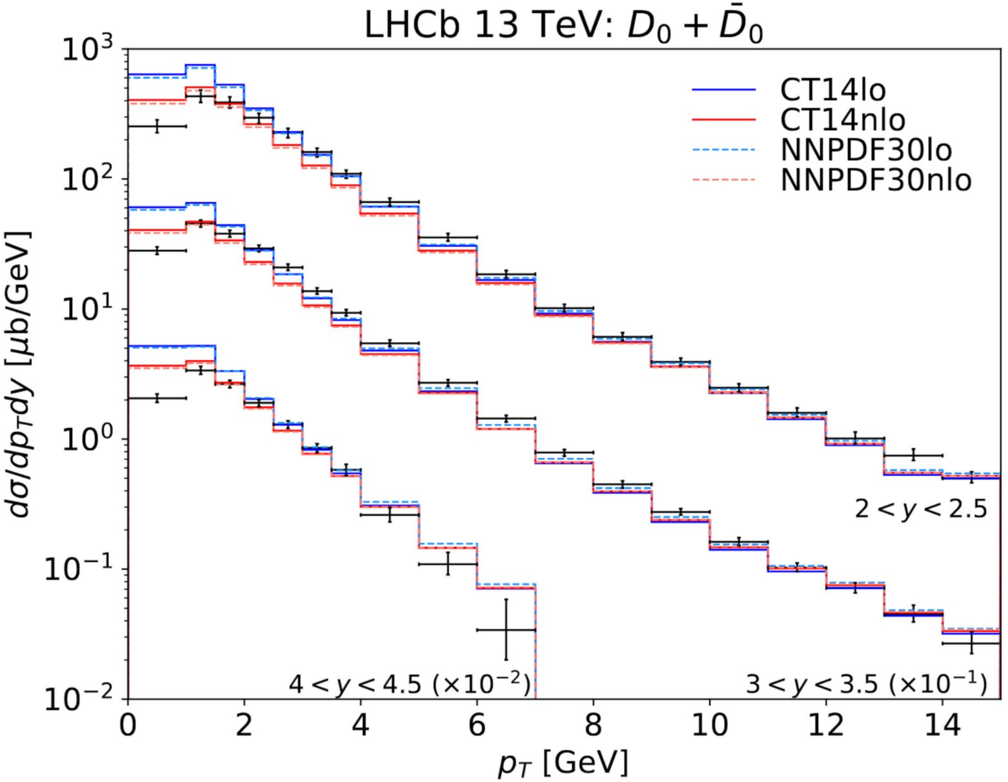


† arxiv:1205.5035

‡ arxiv:hep-ph/0307188

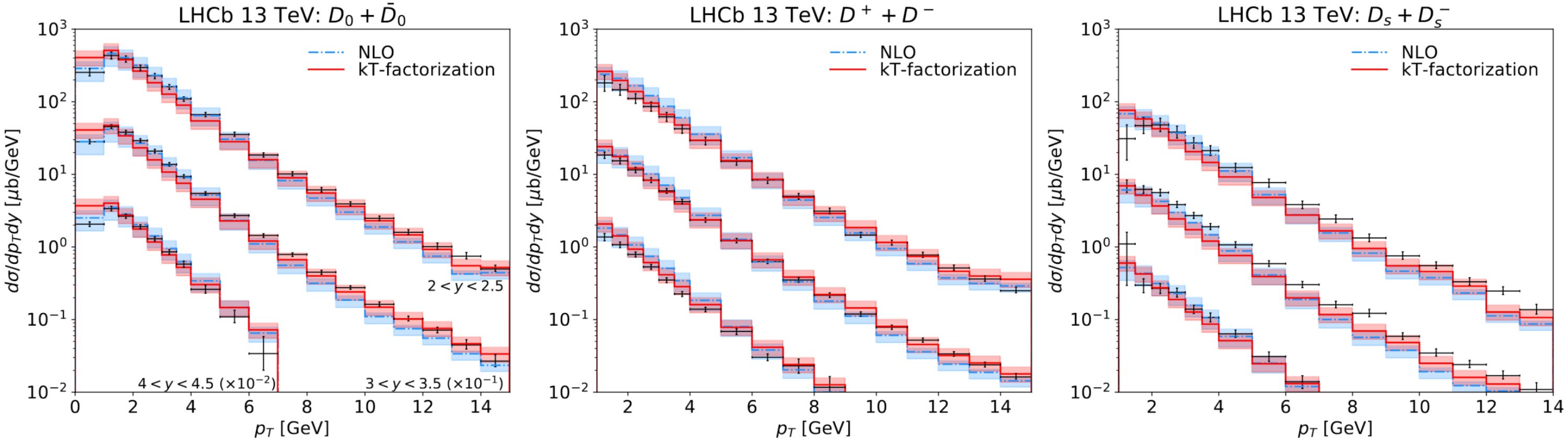
Determining parameters
Fitting $d^2\sigma$ to LHC data

- Different high-x gluon PDF
- Strong coupling variation
- Different scale choices for k_T-factorisation



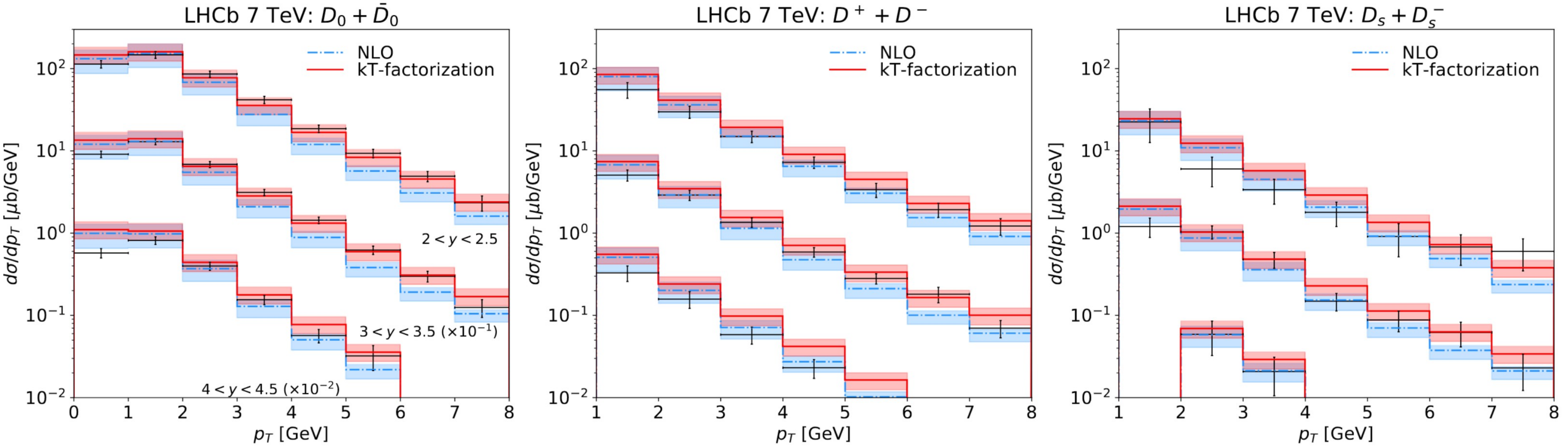
Comparisons

Collinear vs k_T factorisation @ 13 TeV



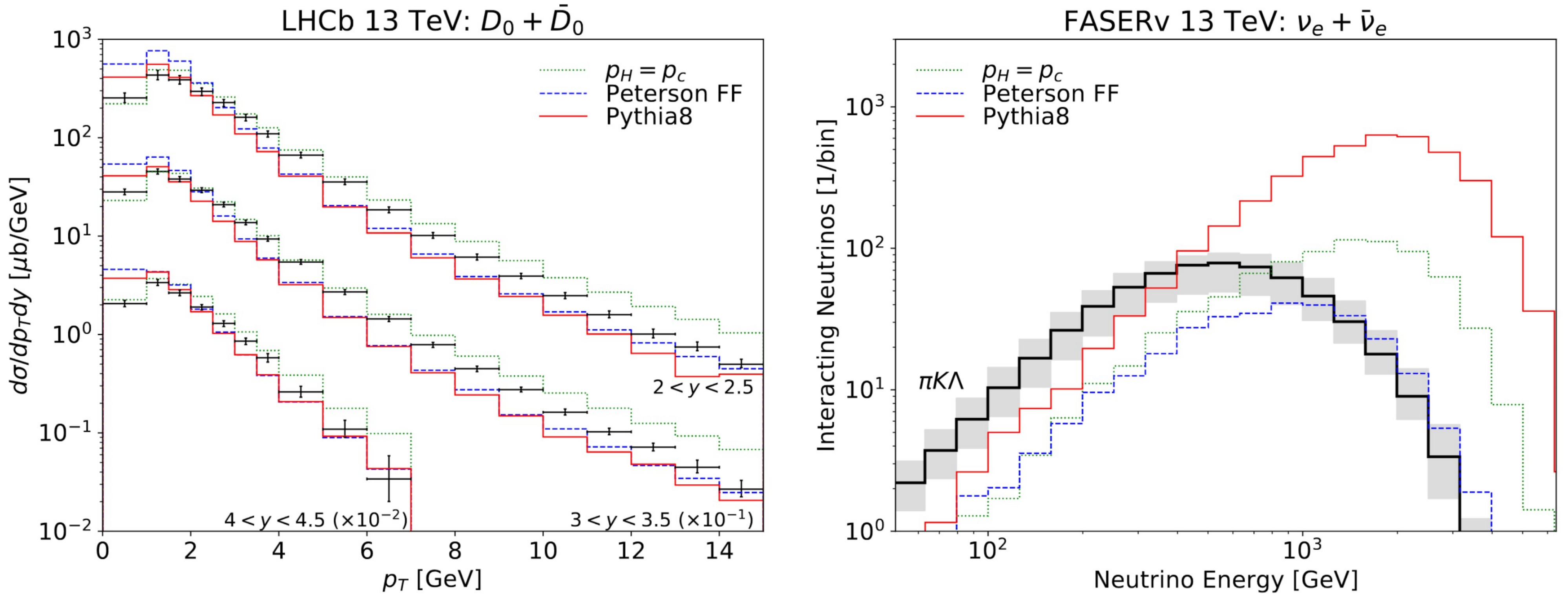
Comparisons

Collinear vs k_T factorisation @ 7 TeV



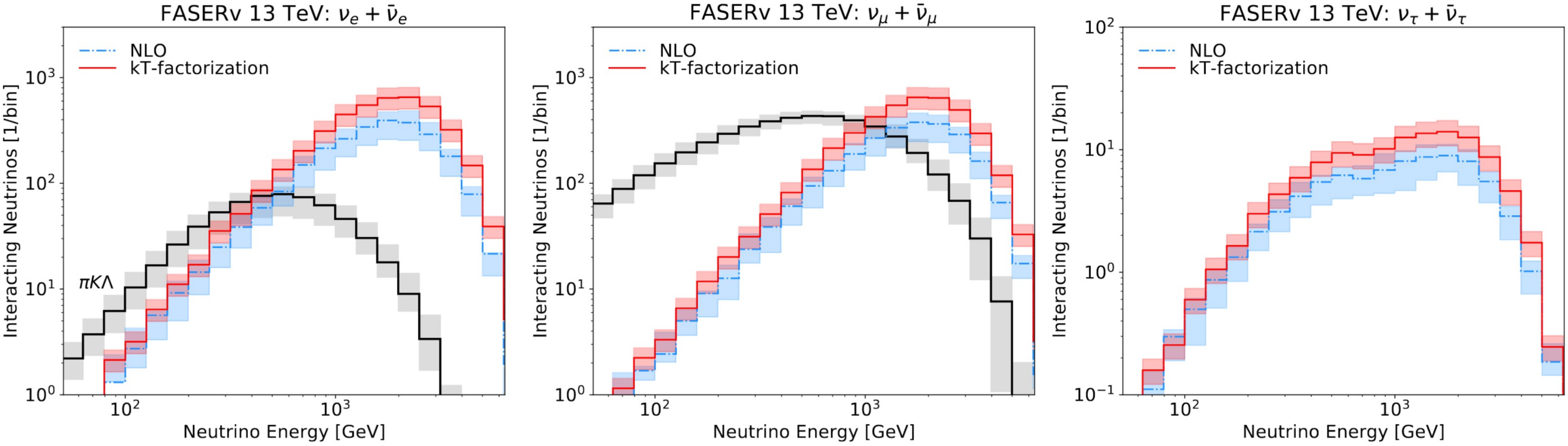
Comparisons

Fragmentation schemes



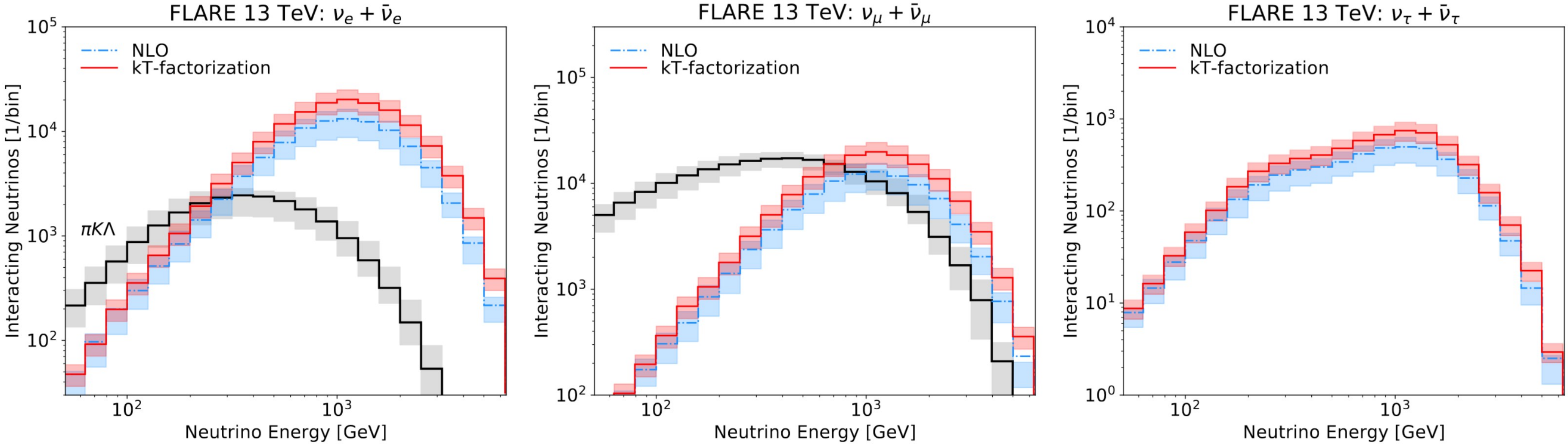
Neutrino fluxes
Estimates for FASERν

4000 ν_e, 4000 ν_μ, and 120 ν_τ @FASERν during LHC Run 3



140,000 ν_e and ν_μ, and 6000 ν_τ @FLARE during HL-LHC

Neutrino fluxes
Estimates for FLARE



Conclusions

Results

- ☑ $pp \to c\bar{c}$: NLO-collinear and k_T factorisations
- ☑ Best-fits against LHCb 13 TeV data; associated uncertainties
- ☑ `Pythia`-based fragmentation scheme to better model high-y, low-p_T hadronisation
- ☑ Consistency check against 7 TeV LHCb data (not used for fits)
- ☑ Predictions for neutrino events at FASERν and, for the future, at FLARE

TODO

- ☐ k_T factorisation: Need NLO-level cross-sections
  - Data-driven k-factor precludes proper comparisons
- ☐ Fragmentation schemes relevant for forward kinematics
- ☐ Comparisons involving different event generators

Outlook

- LHC-FPF driving us into an era of forward neutrino detection
- FASERν and SND@LHC currently operational
  - Proposed detector FLARE during HL-LHC
- ν_e and ν_τ channels provide potential for detecting neutrinos from charmed mesons
- With future collider data, $and\ more\ theoretical\ work$, potential for constraining QCD parameters related to charm
- Improved atmospheric ν background estimates for high-energy neutrino telescopes thanks to better QCD