WG2: Forward Charm Production

Forward Physics Facility

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Work supported in part by the US Department of Energy

Many people involved who bring their wide ranges of expertise to Forward Charm Production.

Leadership of group moving to Anna Stasto.

Data and discussions in WG2: A. Bhattacharya, F. Kling, R. Enberg, I. Sarcevic, A. Stasto, Y.S. Jeong, W. Bai, B. Chauhan, A. Szczurek, F. Silvetti, F. Celiberto, F. Tramontano, H. Otono, L. Buonocore, L. Rottoli, M. Bonvini, M. Lim, P. Nadolsky, R. Maciula, T. Inada, K. Xie, Y. Yuji

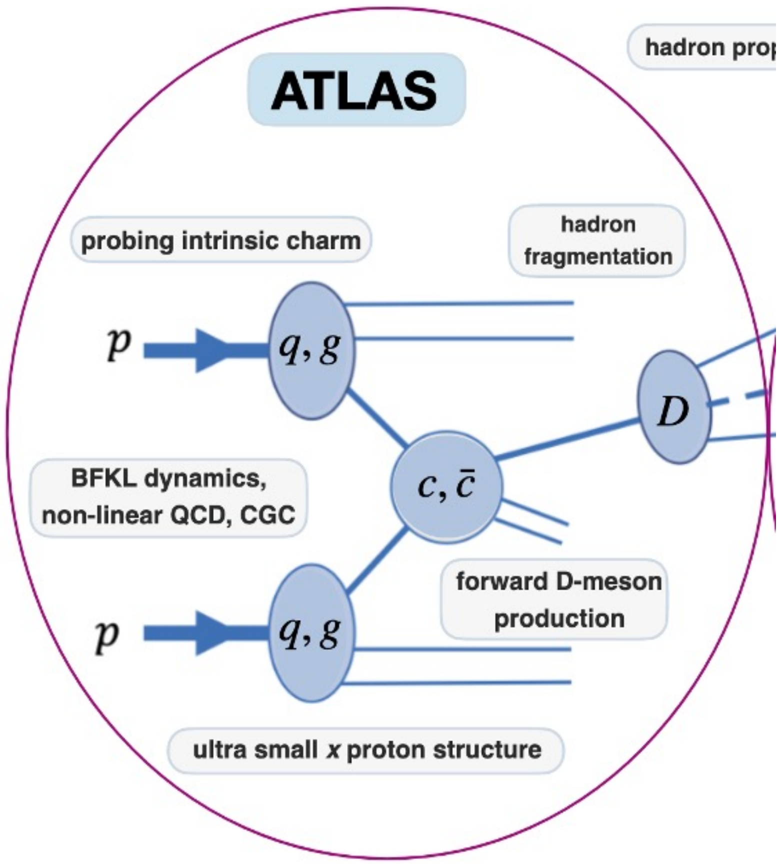
Numerical comparisons from inputs from WG2 with: F. Kling, B. Chauhan

Collaborative work with: M.V. Diwan, M.V. Garzelli, K. Kumar, Y.S. Jeong, W. Bai

FPF WG2 goals include

- Move to quantitative assessment with neutrino measurements (WG1), produce sets of FPF neutrino fluxes with different theory inputs (handling of small x, intrinsic charm, etc).
  - *Compare different predictions of neutrino fluxes from forward charm and unpack where the differences arise: production of charm, fragmentation, decay.*
- Document exiting forward charm production predictions and their corresponding neutrino flux evaluations.
- Longer term:
  - Project how measurements of other experiments could impact predictions of neutrino fluxes at the FPF.
  - Articulate further the physics potential associated with measurements of FPF neutrino fluxes.

Forward charm to neutrinos



- PDFs as they pertain to neutrino production through charm production and decay
  - small-x: gluons, BFKL, saturation, resummation
  - large-x: gluons, intrinsic charm
- role of transverse momentum
- fragmentation to charm hadrons
- potential links to astroparticle physics: air showers and prompt atmospheric neutrinos

FPF working groups: WG2 closely related to WG1 (Rojo presentation) and connected to WG3 (Soldin presentation).

Strategy: consider LHCb charm production @ 13 TeV and neutrino fluxes at FPF

https://github.com/KlingFelix/ForwardCharm

- charm hadron distributions in pT and y from different groups/sources
- charm decays in rest frame using Pythia8 – all the same decays
- boost back to collider frame, pick neutrinos passing through detector cross section

1a. Take out fragmentation differences:

- comparisons of charm quark production (same fragmentation, same decays)
- comparisons between similar approaches, e.g., kT factorization

Strategy: consider LHCb charm production @ 13 TeV and neutrino fluxes at FPF

Hadronic interaction models: Sibyll 2.3d, DPMJET 3.2019, Pythia 8, Pythia 8-BLC (string formation beyond leading color)-*Felix Kling (see also Kling & Nevay, PRD 104 (2021) 11)*

MC generators @LO: Pythia 8, Pythia 8-BLC, Herwig 7 – *Peter Reimitz*

kt factorization with and without gluon saturation, with 2 fragmentation schemes (Peterson and BLC) – *Stasto, Bhattacharya, Kling, Sarcevic (arXiv2306.01578)*

kt factorization with MRW unintegrated gluon uPDFs, hybrid, hybrid with KS-linear uPDFs, plus intrinsic charm, recombination – *Maciula, Szczurek (PRD 107 (2023) 034002)*

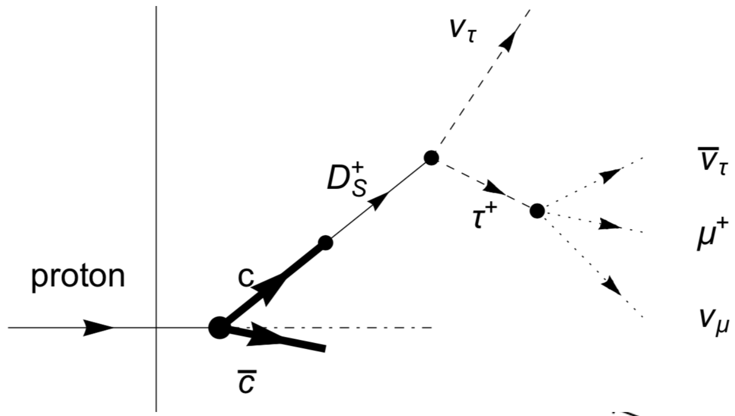
NLO collinear factorization, with 2 fragmentation schemes -- *Stasto, Bhattacharya, Kling, Sarcevic (arXiv2306.01578)*

NLO collinear factorization, with kT smearing – *Jeong, Bai, Reno (similar to Bai, Diwan, Garzelli et al, JHEP 06 (2022) 148, JHEAp 34 (2022) 212)*

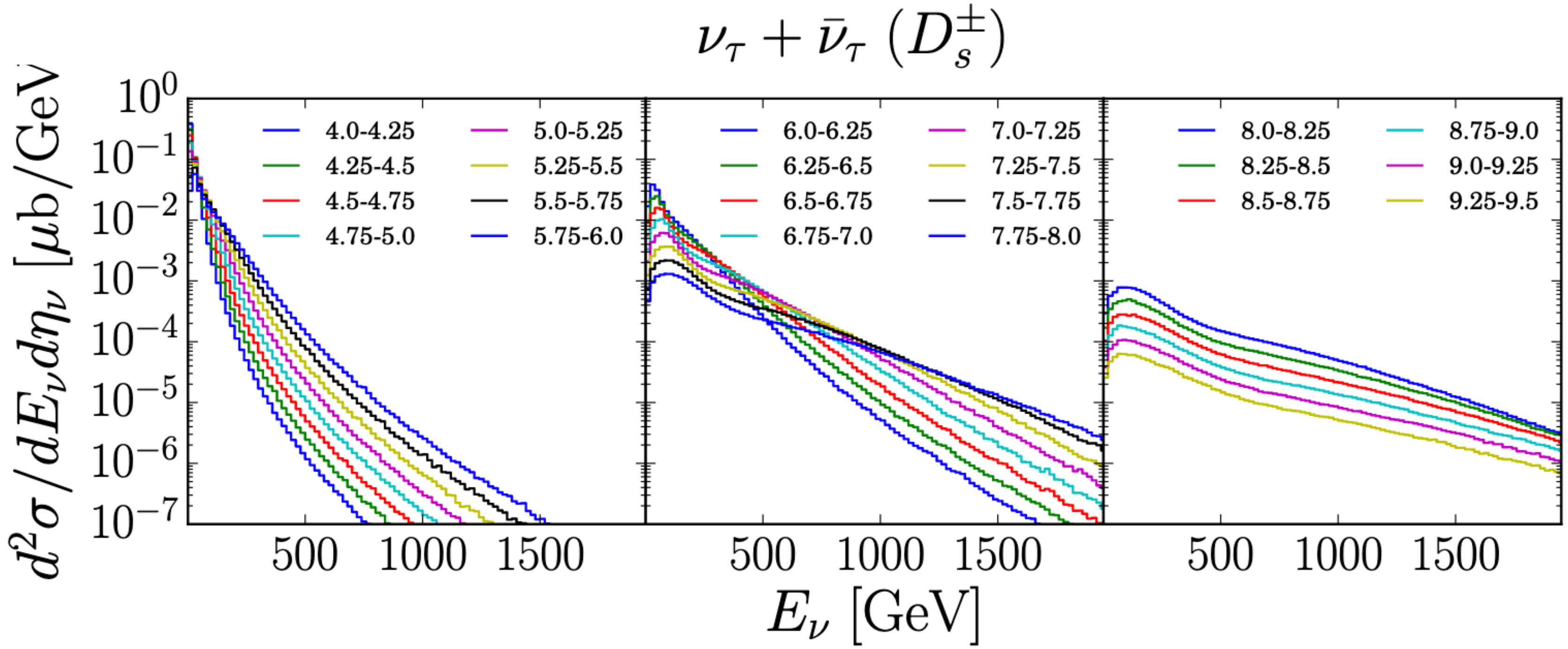
NLO collinear factorization, intrinsic charm in PDFs, *Keping Xie, et al*.

NLO collinear factorization with NLL_x PDFs, parton showers – *Buonocore and Rottoli (in preparation)*

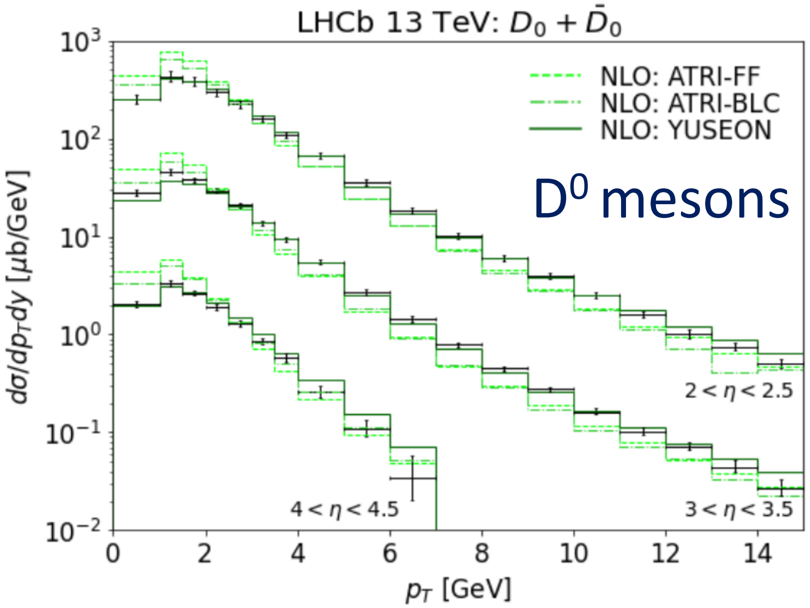
Reminder, $\nu_\tau + \bar{\nu}_\tau$ from D_s

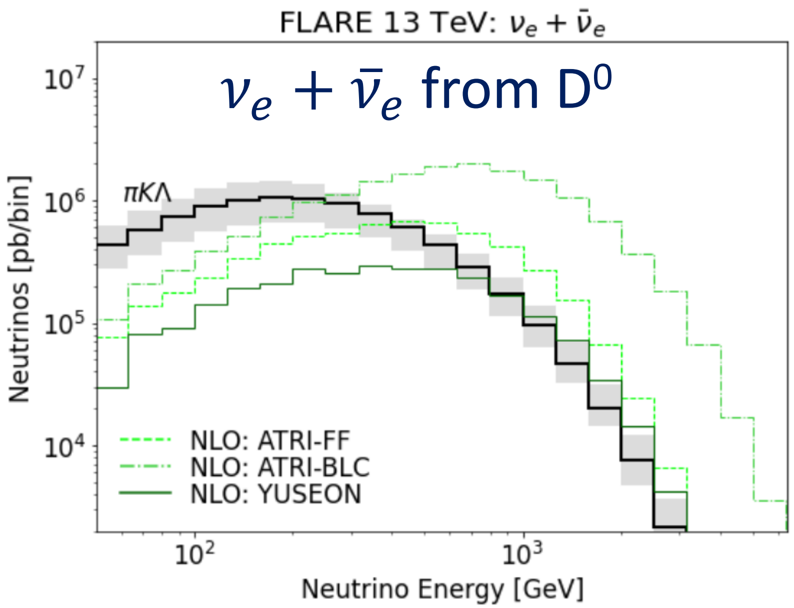


- There are more $\nu_e + \bar{\nu}_e$ than $\nu_\tau + \bar{\nu}_\tau$.
- Origins of $\nu_e + \bar{\nu}_e$ from charm will be easier than origins of $\nu_\mu + \bar{\nu}_\mu$.



Bai, Diwan, Garzelli, Jeong et al., JHEAp 34 (2022) 212





Sample comparisons: NLO QCD @LHCb and FLArE

Differences:

- fragmentation (function, and how)
- renormalization and factorization scales
- kT smearing in one
- PDFs, scales

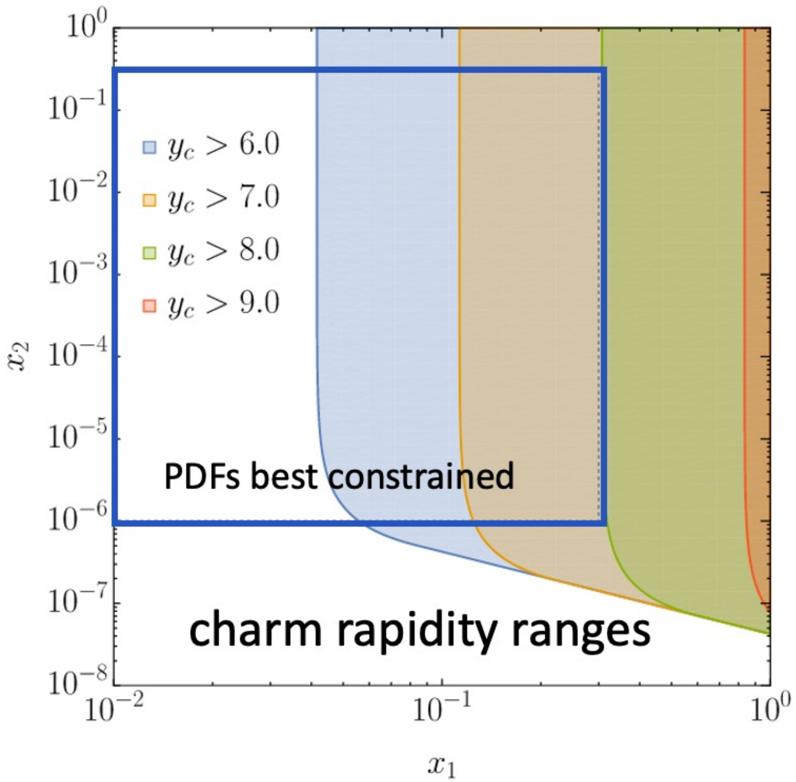
(PDF scale dependence variations cover LHCb data range, but lead to large uncertainty in neutrino flux.)

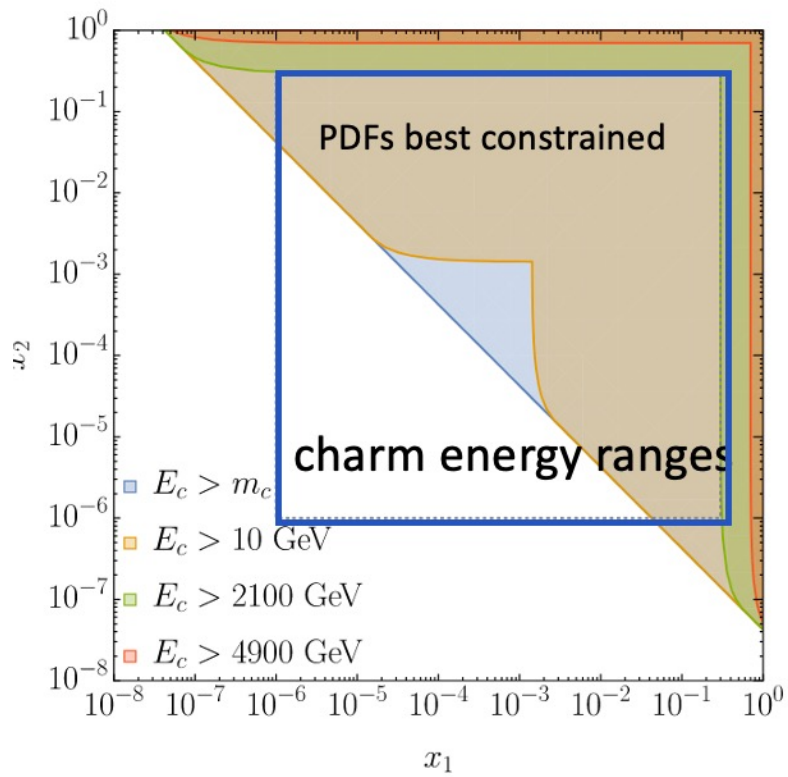
Electron neutrinos they produce.

(Colored histograms from charm, black histograms from light mesons, Lambda.)

Jeong, Bai, Reno (similar to Bai, Diwan, Garzelli et al, JHEP 06 (2022) 148, JHEAp 34 (2022) 212) NLO+kT smearing
Bhattacharya, Kling, Sarcevic, Stasto, (arXiv2306.01578) NLO w FF, BLC (color recombination beyond leading color)

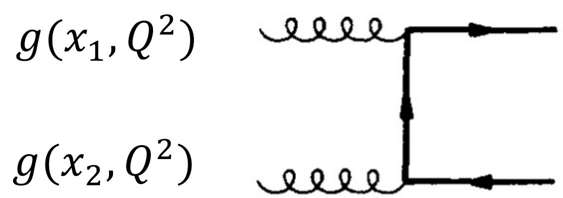
Small-x and large-x: PDFs in new kinematic regimes





<u>Reminder</u>

- perturbative QCD at next-to-leading order is dominated by gluon fusion, e.g.,



$x_1 \gg x_2$

Figs: W. Bai, M. V. Diwan, M. V. Garzelli, K. Kumar, Y. S. Jeong & MHR. (2212.07865).

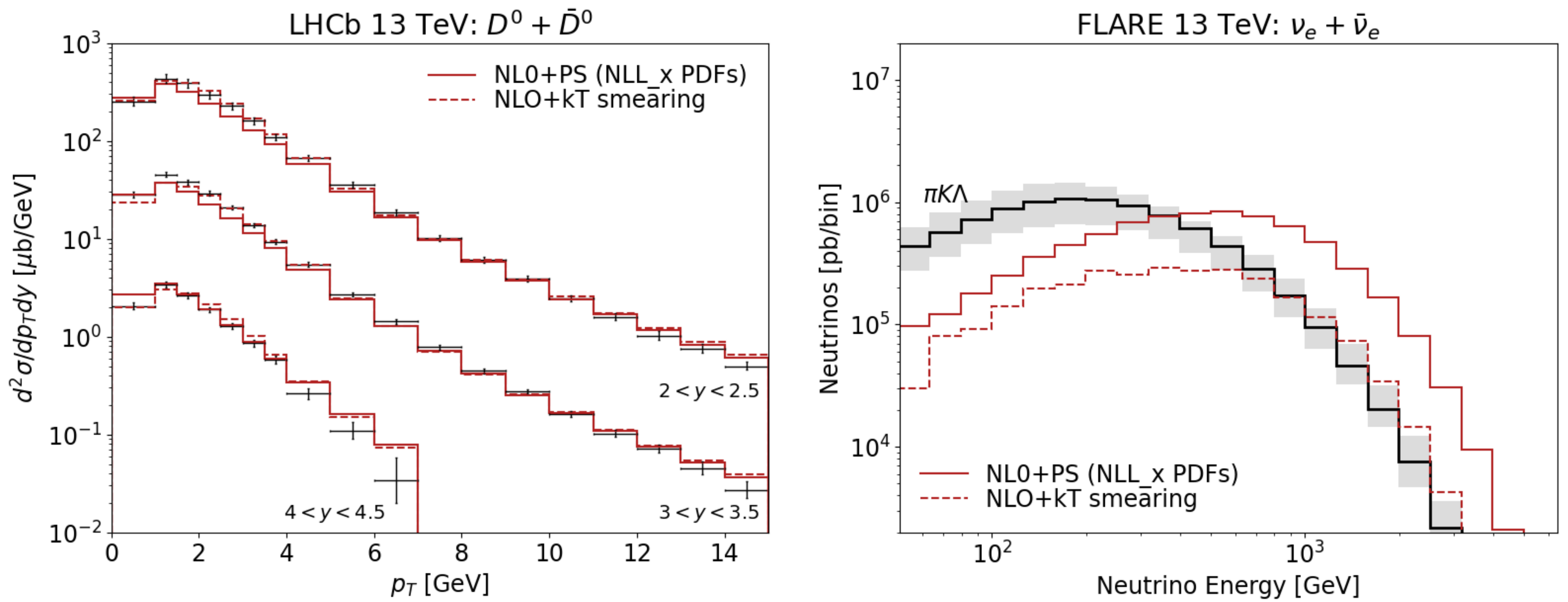
High rapidity, high charm energy probes new region of gluon PDFs.

Small-x_2: need to consider resummation of $\alpha_s \ln(\frac{1}{x})$.

Sample comparisons: NLO QCD @LHCb and FLArE

Differences: primarily in PDFs, one has NLL_x PDFs sum $\ln(1/x_2)$.

Both: collinear factorization.

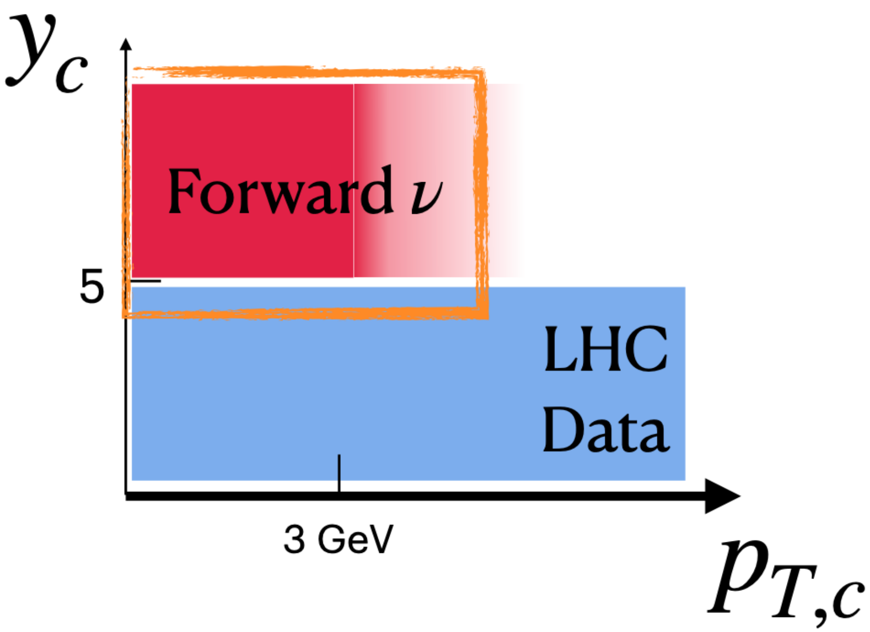


Jeong, Bai, Reno (similar to Bai, Diwan, Garzelli et al, JHEP 06 (2022) 148, JHEAp 34 (2022) 212)
NLO+kT smearing

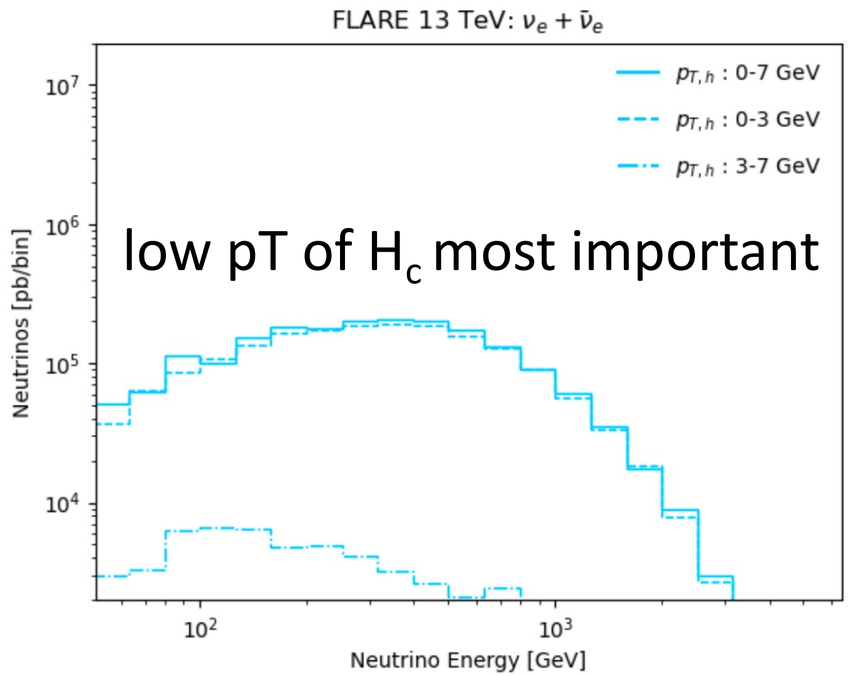
L. Buonocore and L. Rottoli, in preparation (2023) NLO+PS (NLL_x PDFs)

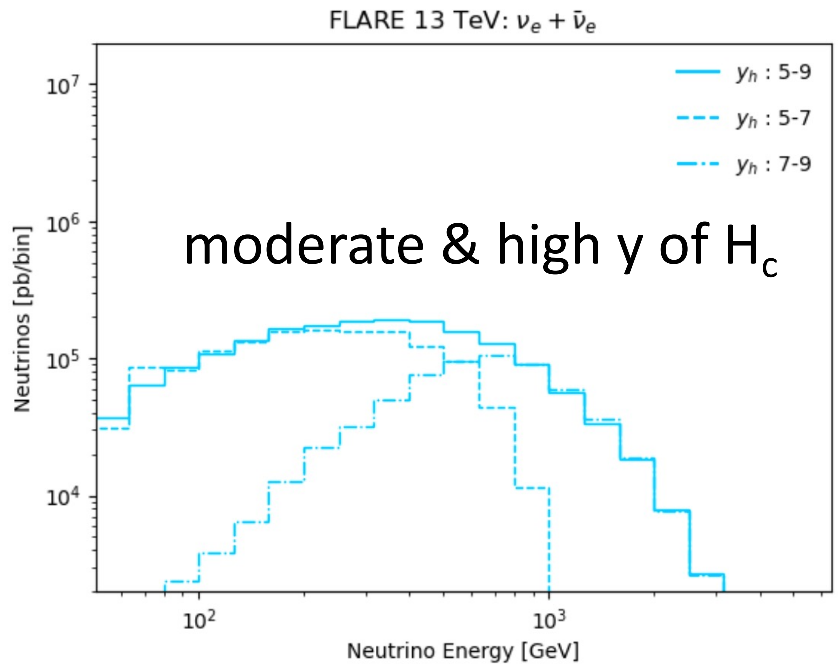
Histograms almost the same for most of LHCb range, much different at FLArE.

What kinematic region?



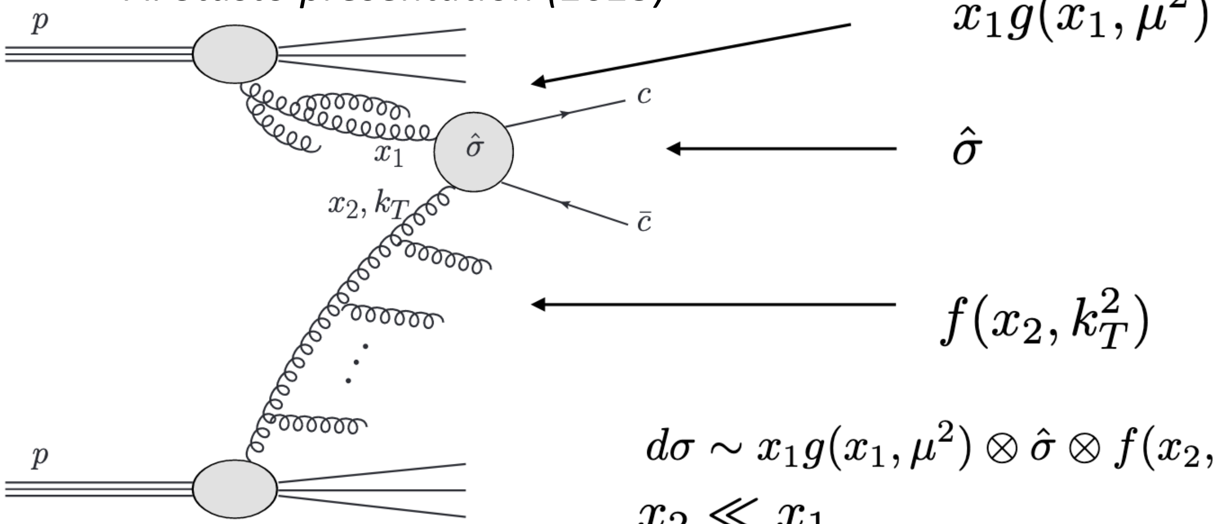
B. Chauhan presentation (2023)





k_T factorization approach

A. Stasto presentation (2023)



$$d\sigma \sim x_1 g(x_1, \mu^2) \otimes \hat{\sigma} \otimes f(x_2, k_T^2)$$

$$x_2 \ll x_1$$

Martin-Ryskin-Stasto prompt neutrino production from charm

- Forward charm means a large *x* (x_1) and a small *x* (x_2).
- Here, $\alpha_s \ln(\frac{1}{x})$ resummation implemented in k_T factorization approach.
- One gluon off-shell, k_T dependent unintegrated PDF

Kutak-Sapeta model:

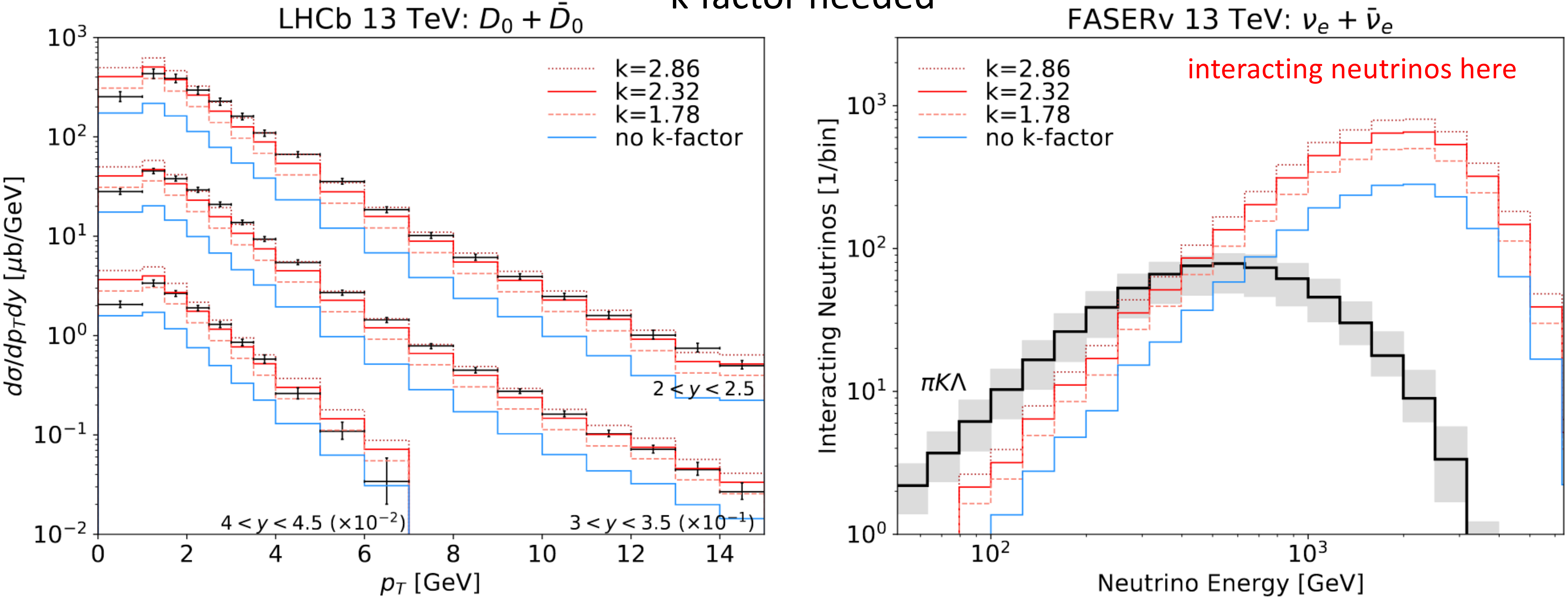
• based on LO BFKL + LO DGLAP, kinematical constraint, corresponds to taking large part of NLO BFKL into account.

Results with and without gluon saturation – some preference to saturation.

Bhattacharya, Kling, Sarcevic, Stasto, (arXiv2306.01578)

k_T factorization approach

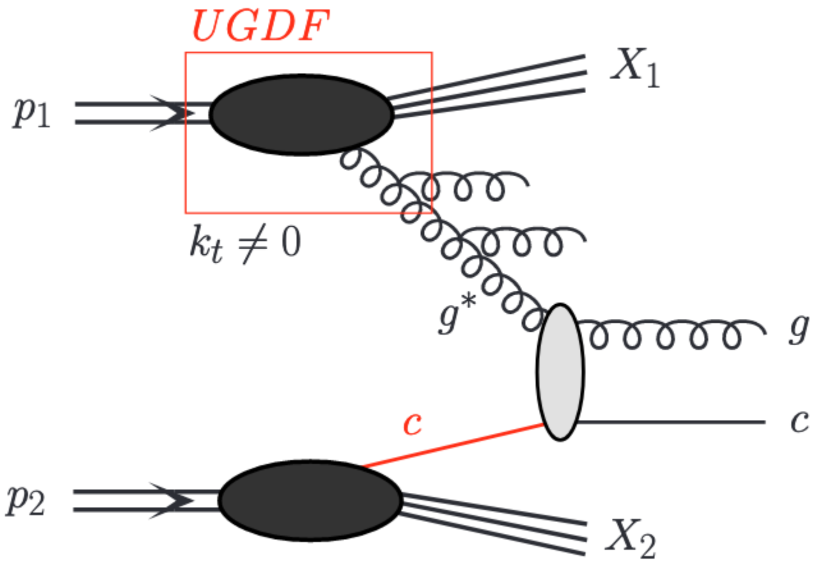
k-factor needed



(see also Maciula, Szczurek, PRD 107 (2023) 034002)

Bhattacharya, Kling, Sarcevic, Stasto, (arXiv2306.01578)

Intrinsic charm in PDFs



Maciula, Szczurek, Phys. Rev. D 107 (2023) 034002

Here: large x (x_2) and a small x (x_1)

Intrinsic charm PDFs for large x

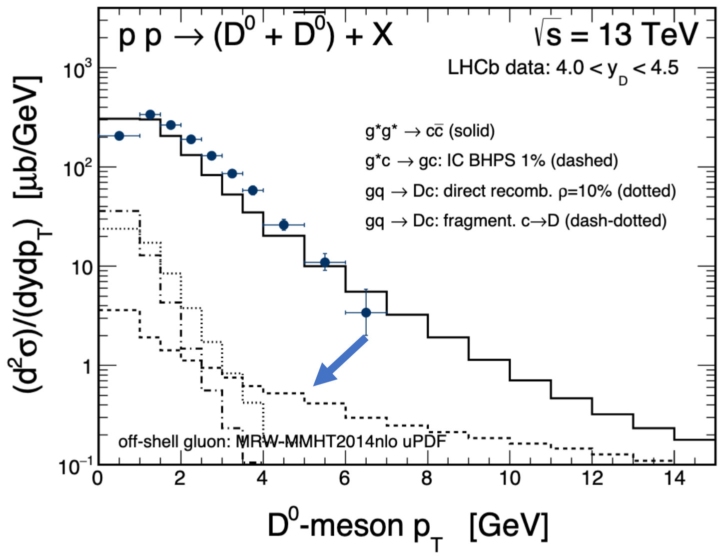
e.g., *Dulat et al., Phys. Rev. D 89 (2014) 073004; Hou et al., JHEP 02 (2018) 059; Ball et al., Nature 608 (2022) 483.*

FPF is particularly sensitive to enhancement of $c(x_2,Q)$ for large x_2 in contrast to most more central processes.

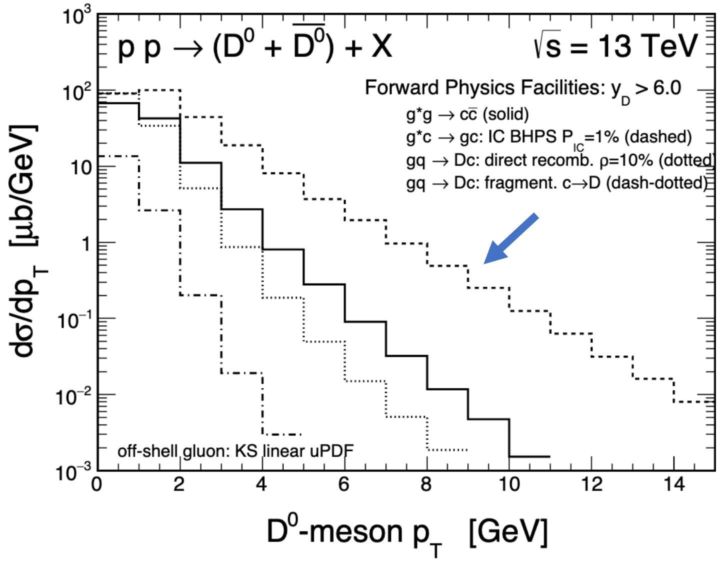
Intrinsic charm in PDFs

low pT to forward neutrinos

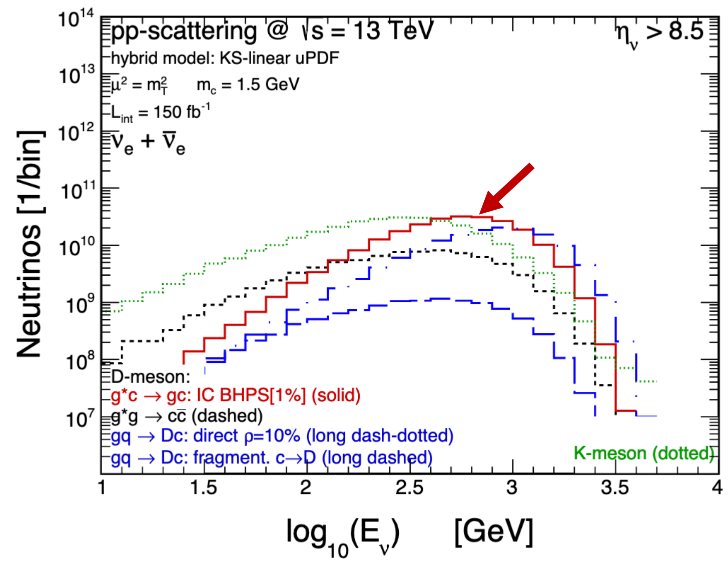
dashed histograms: intrinsic charm contributions



LHCb



more forward hadrons



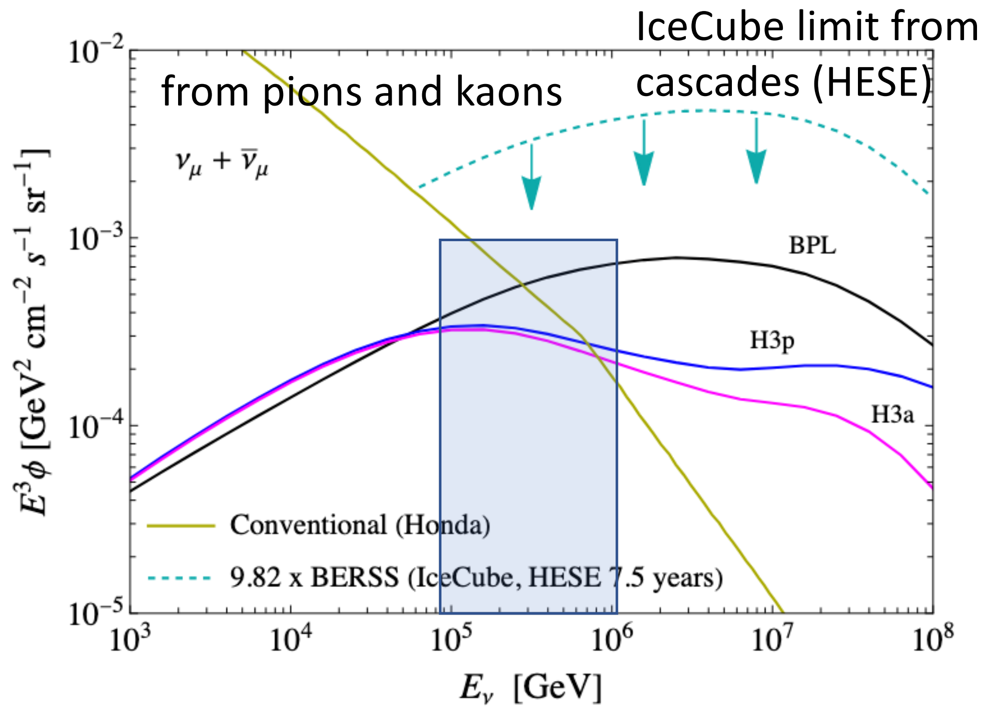
FPF

Maciula, Szczurek, Phys. Rev. D 107 (2023) 034002

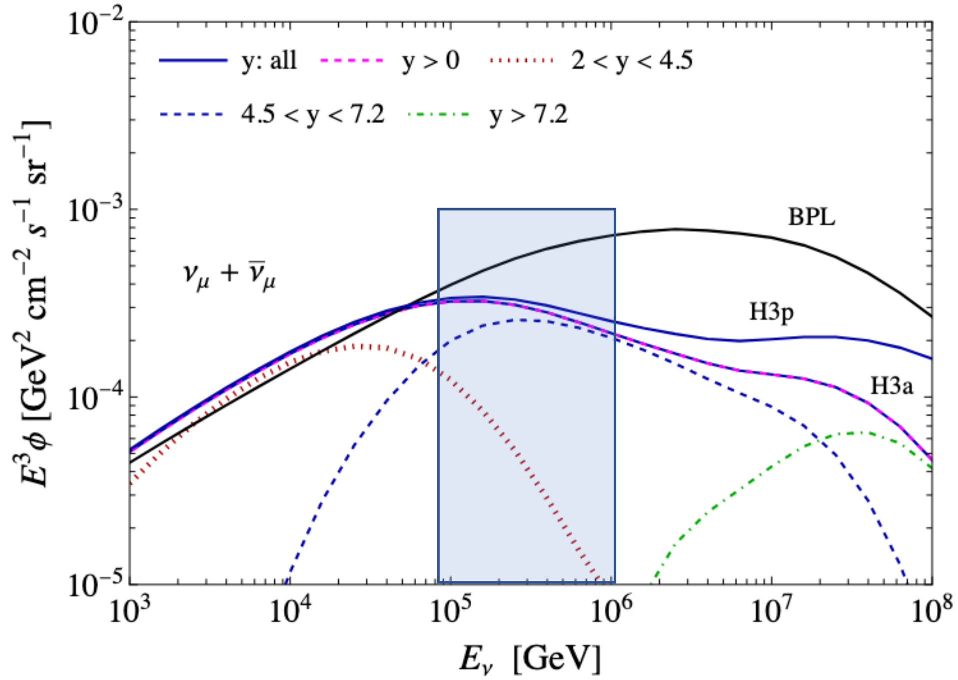
FPF neutrinos and atmospheric charm

Steeply falling CR flux, favors forward hadron production. How forward?

atmospheric neutrino flux
see scaling



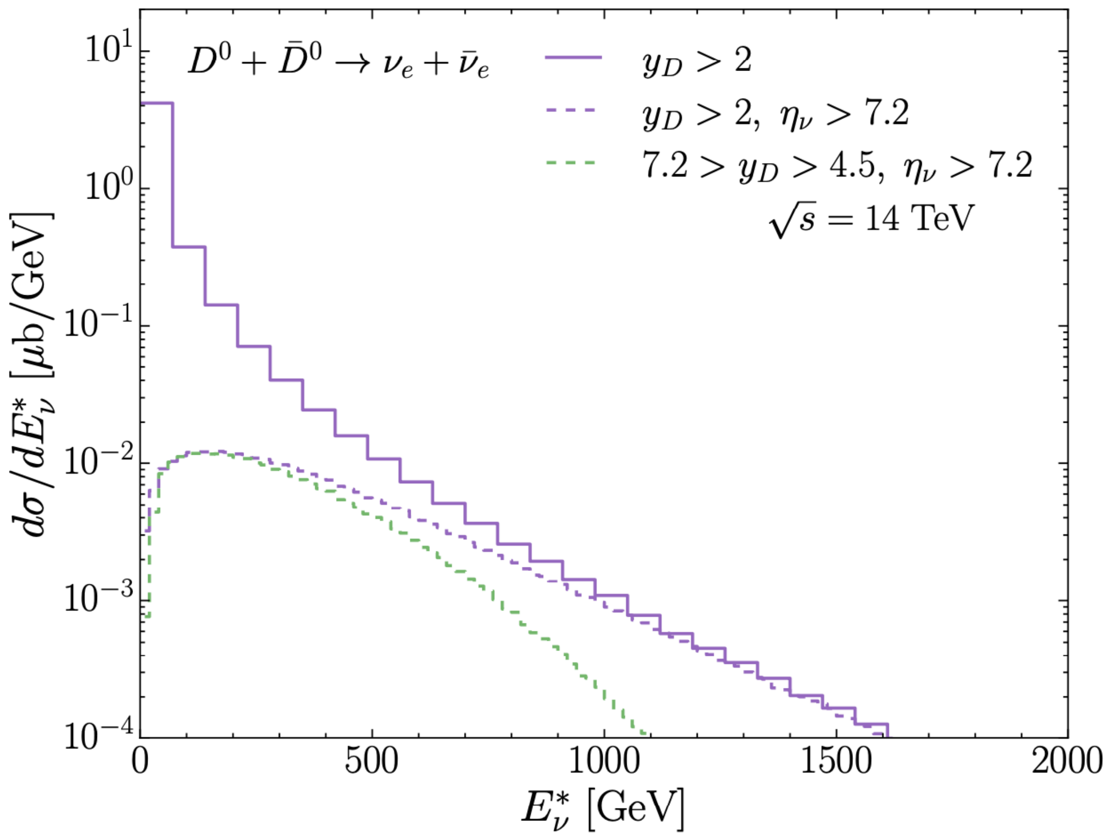
From charm hadrons with $4.5<y_C<7.2$ in the equivalent collider frame.



neutrinos from charm (prompt atm nu flux): 2 CR flux models +broken power law (BPL)

Bai, Diwan, Garzelli, Jeong et al., arXiv:2212.07865

FPF neutrinos and atmospheric charm



@LHC

Energy distribution of neutrinos from D_0+cc from different D_0 rapidities.

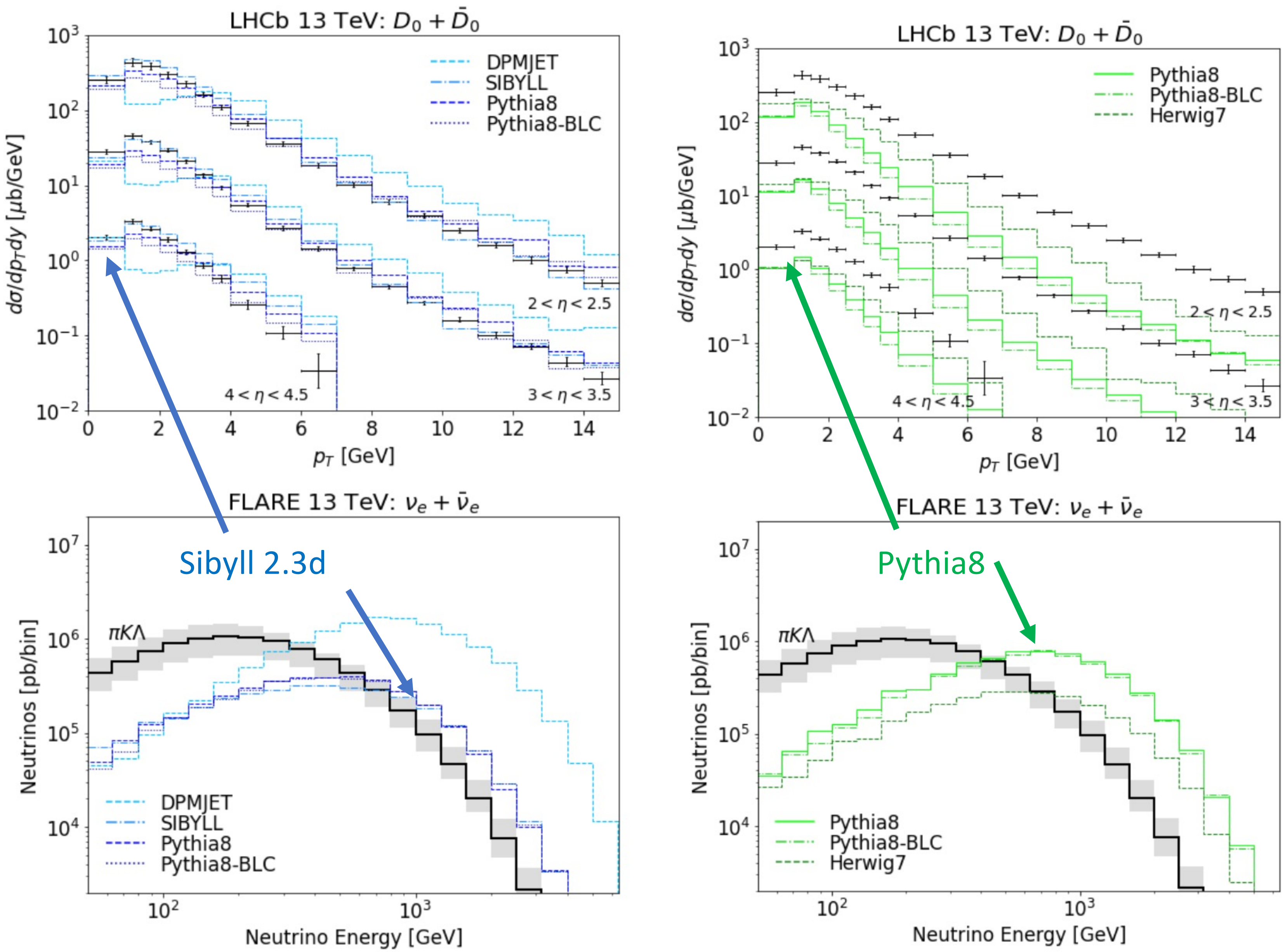
- all neutrino η_ν from 2<y_D
- $\eta_\nu > 7.2$ from 2<y_D
- only neutrino η_ν>7.2 from 4.5<y<7.2

Conclusion: Since most of the neutrinos with $E_\nu < 700$ GeV and η_ν>7.2 come from charm mesons with 4.5<y_D<7.2, there is a direct connection to the prompt atmospheric neutrino flux (from charm).

Bai, Diwan, Garzelli, Jeong et al., arXiv:2212.07865

Comments

- NNLO charm production needed (available for *b* quarks, Catani et al.) to reduce scale dependence in collinear approach. At NLO, are there degeneracies with scale choices for LHCb but not for FPF neutrinos?
- Agreement of theory with most of the LHCb p_T range does not adequately constrain FPF neutrino predictions. FPF neutrino measurement can do something new.
- Low p_T is very important – intrinsic transverse momentum, k_T factorization, parton showering, fragmentation effects can all have low p_T effects. Can E_ν, η_ν dependent distributions (different η_ν bins) help us better understand charm quark and hadron production?
- Can we use the shapes of the neutrino distributions to distinguish physics input?
- Measurements: combined flux and cross section. Need to understand flux from light hadrons, too.



$\nu_e + \bar{\nu}_e$ from D^0 Monte Carlos

D^0 mesons

Except for Sibyl 2.3d, not tuned for charm production.

Green - LO

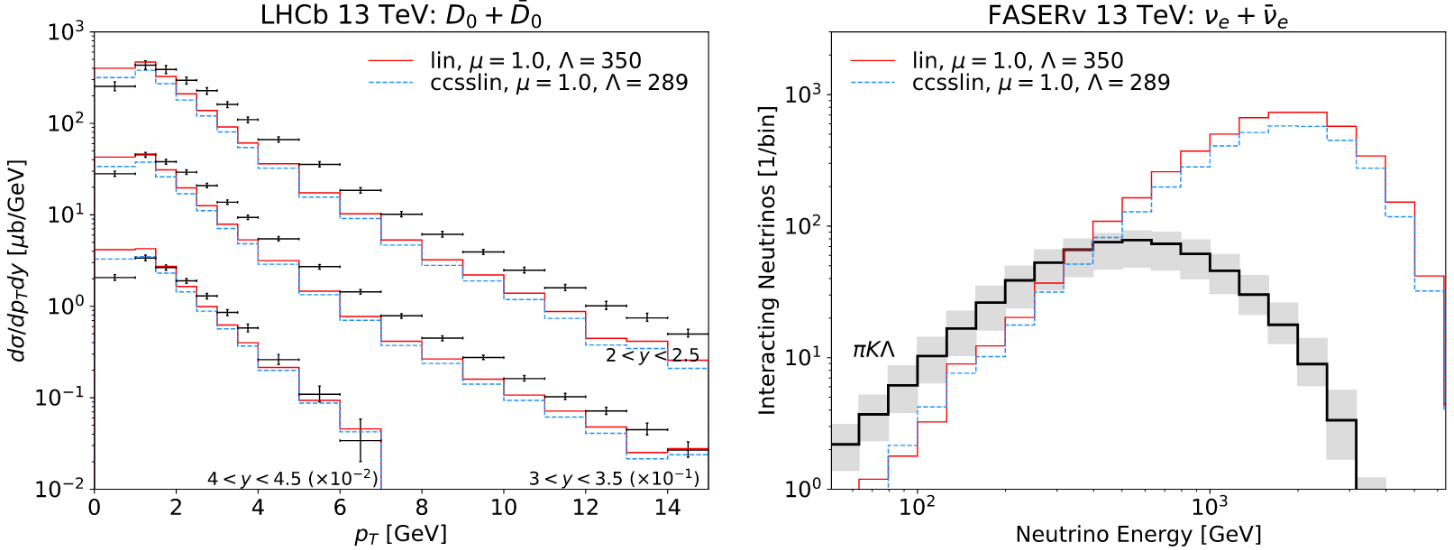
Electron neutrinos they produce.

Pythia8 low for LHCb, high for neutrinos at FLArE.

Comparison KS vs CCSS gluon

A. Stasto presentation (2023)

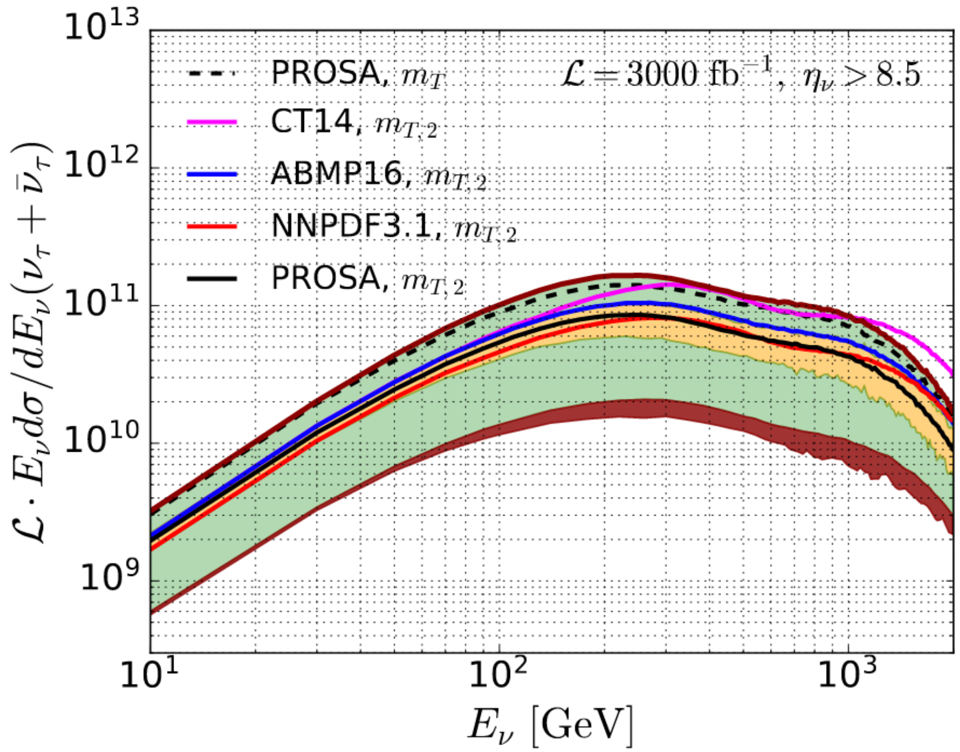
Comparison between Kutak-Sapeta and CCSS type gluon (Li-Stasto)
CCSS gluon: includes full NLO BFKL with DGLAP, resummed



Rather small differences, some change in shape in p_T

Bhattacharya, Kling, Sarcevic, Stasto, (arXiv2306.01578)

- Updated unintegrated PDFs don't change results much.
- Here: linear evolution. Some preference for nonlinear evolution.
- Consistent with other kT-factorization results. [*Maciula, Szczurek, PRD 107 (2023) 034002]*



Green: QCD scale uncertainty

Feng et al., J Phys. G 50 (2023) 030501