Small x prediction for forward charm production

and implications for neutrino spectrum at FASER

Anna Staśto

PennState
Eberly College of Science

in collaboration with Atri Bhattacharya, Felix Kling, Ina Sarcevic

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Outline

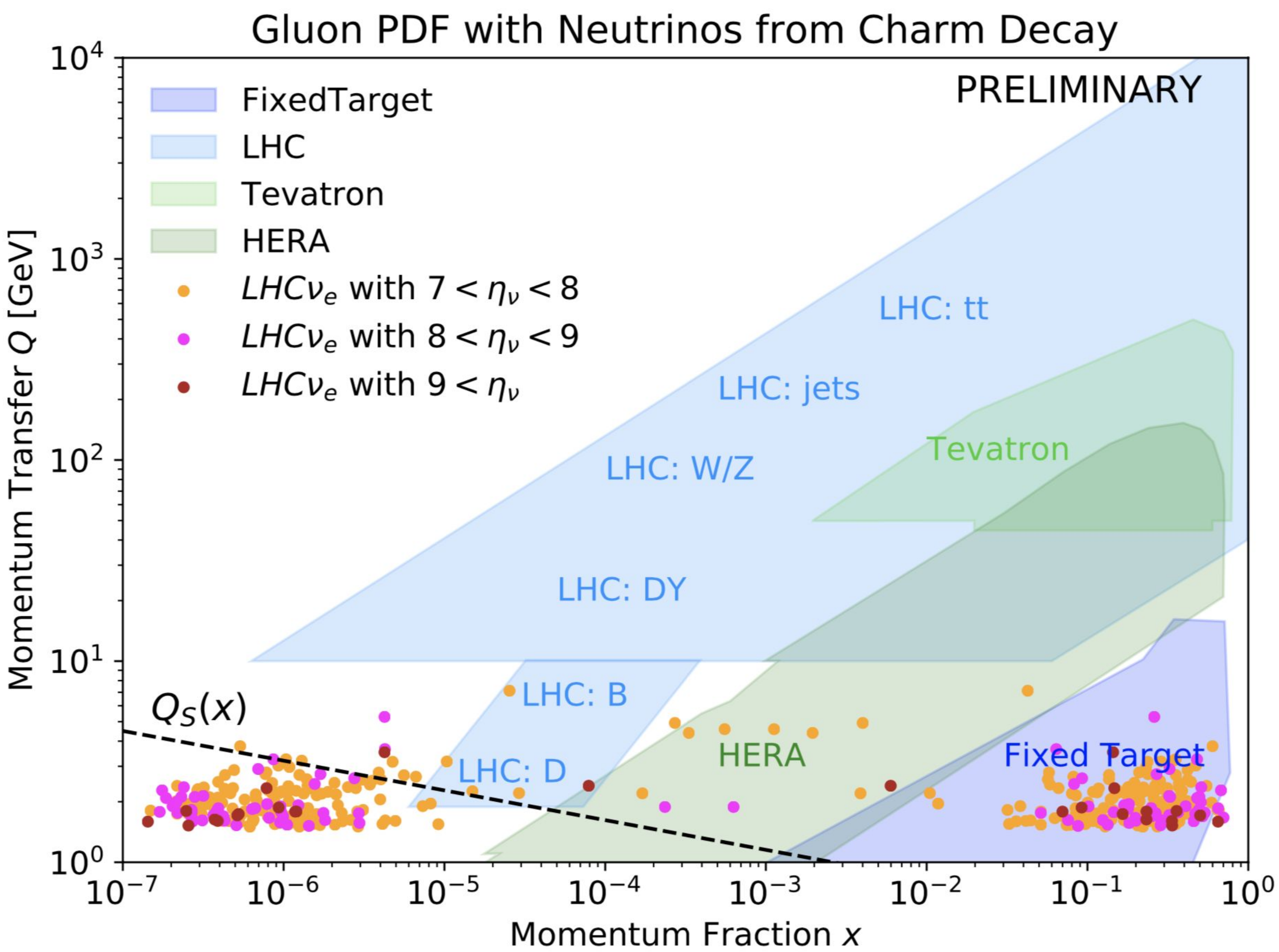
- Motivation for calculation with small x dynamics in the forward region
- Framework for *charm production*: k_T factorization + small x resummation with and without saturation
- Results: neutrino spectrum
- Other issues: fragmentation in the forward region
- Outlook

Motivation

Small x region: BFKL Pomeron, saturation, diffraction

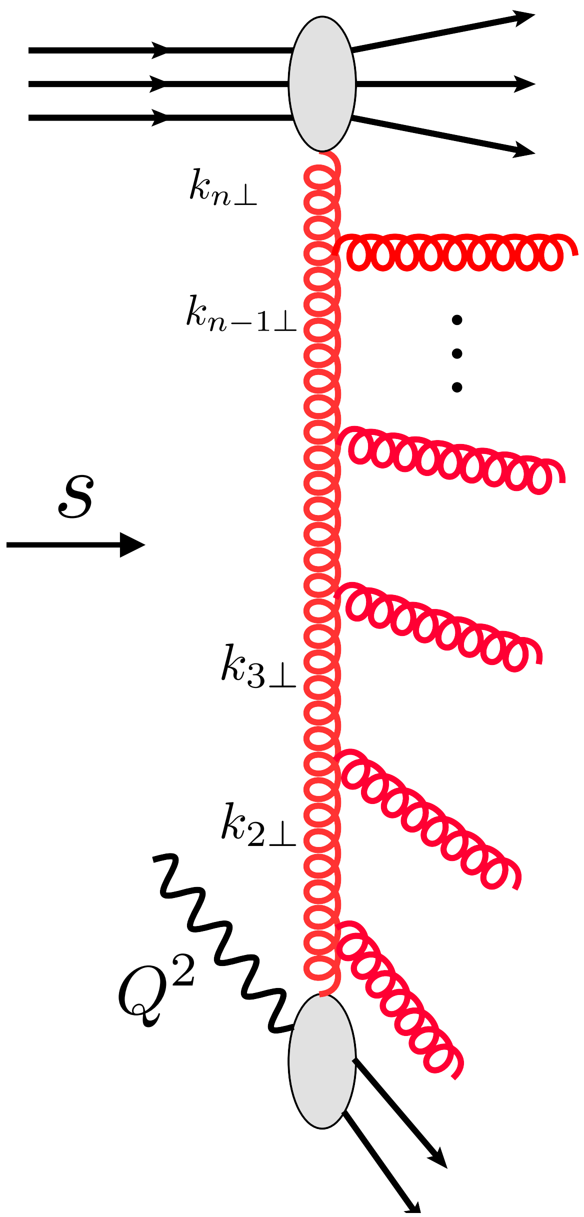
LHC and dedicated experiment FASER has potential to explore the extremely small x

(x,Q) phase space



Collinear approach

$\gamma^* N$ as a template



Large parameter

$$Q^2 \to \infty$$

s total energy is fixed

Probing small distances

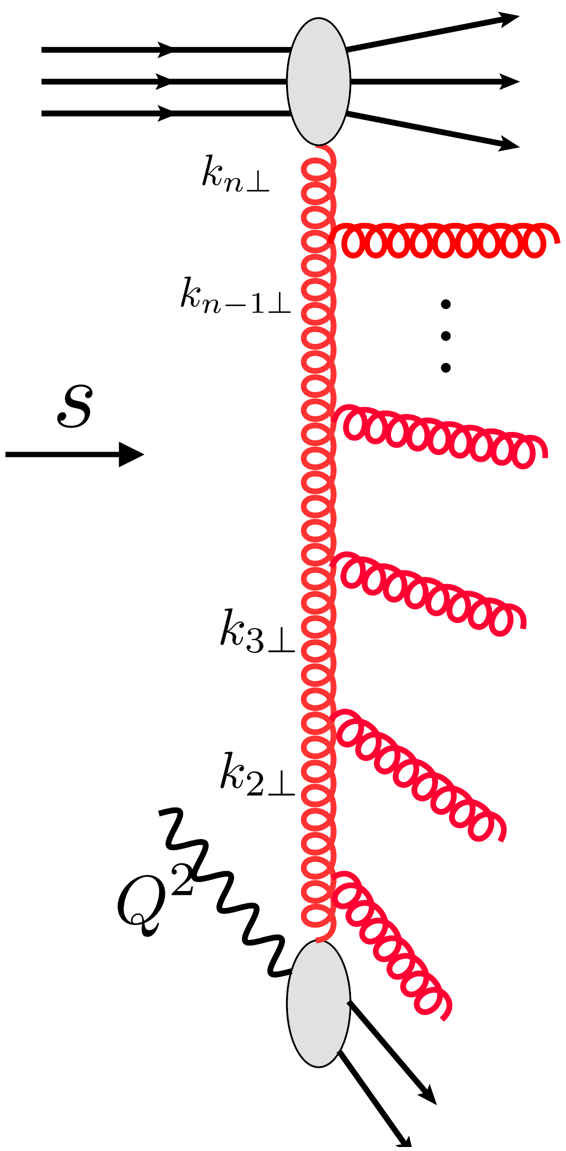
Strong ordering in transverse momenta

$$Q^2 \gg k_{1\perp}^2 \gg k_{2\perp}^2 \gg k_{3\perp}^2 \cdots \gg k_{n\perp}^2$$

Resummation of large logarithms

$$\int_{\mu_0^2}^{Q^2} \frac{dk_{1\perp}^2}{k_{1\perp}^2} g^2 \int_{\mu_0^2}^{k_{1\perp}^2} \frac{dk_{2\perp}^2}{k_{2\perp}^2} g^2 \int_{\mu_0^2}^{k_{2\perp}^2} \frac{dk_{3\perp}^2}{k_{3\perp}^2} g^2 \cdots \int_{\mu_0^2}^{k_{n-1\perp}^2} \frac{dk_{n\perp}^2}{k_{n\perp}^2} g^2 \simeq \left(g^2 \log \frac{Q^2}{\mu_0^2} \right)^n$$

Collinear approach



DGLAP evolution equation for parton densities

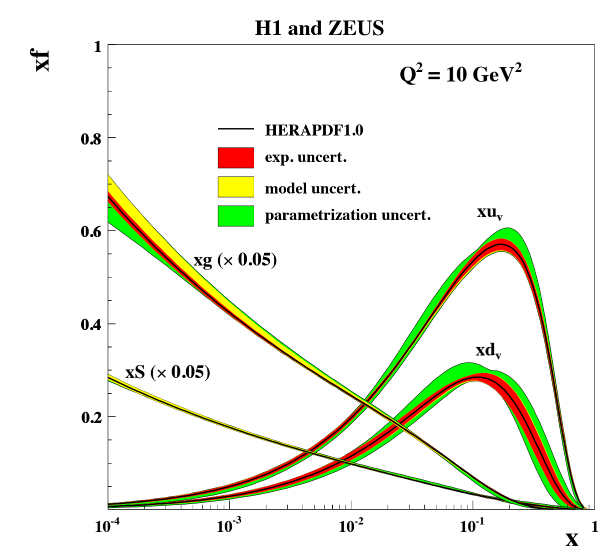
$$\frac{\partial f_i(x,Q^2)}{\partial \log(Q^2)} = \sum_j \int_x^1 \frac{dz}{z} P_{j\to i}(z) f_j(\frac{x}{z},Q^2)$$

Splitting functions calculated perturbatively

$$P_{j\to i}(z) = \alpha_s P^{(LO)}_{j\to i}(z) + \alpha_s^2 P^{(NLO)}_{j\to i}(z) + \alpha_s^3 P^{(NNLO)}_{j\to i}(z) + \ldots$$

Parton densities: distributions in longitudinal momenta at a given scale

$$f_i(x,Q^2)$$

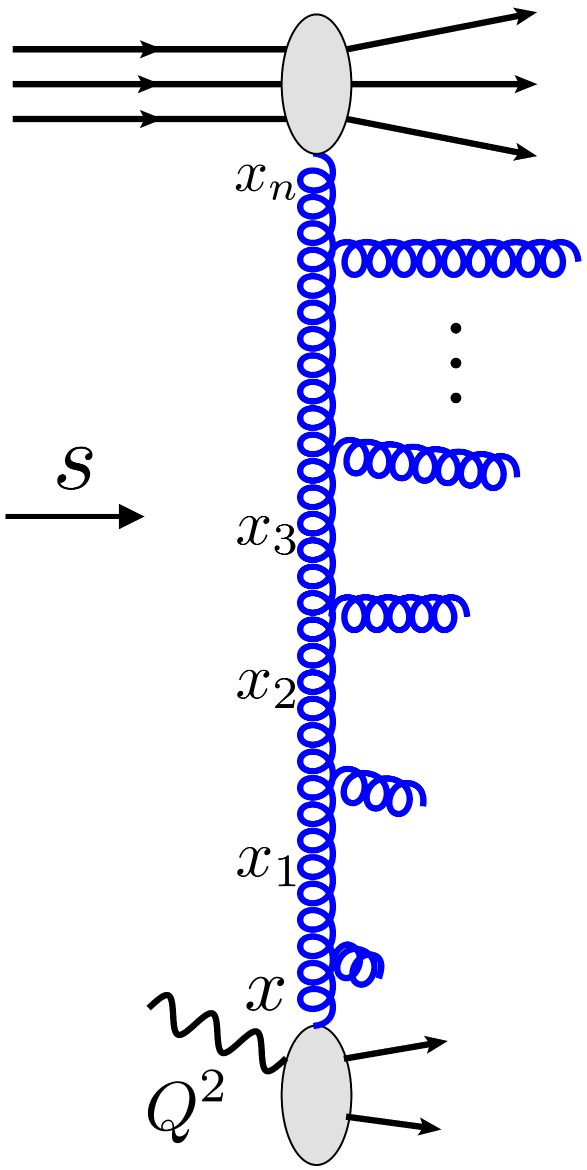


Collinear factorization of the cross section

$$d\sigma(x,Q^2) = \sum_i f_i \otimes d\hat{\sigma}^i + \mathcal{O}(\Lambda^2/Q^2)$$

$d\hat{\sigma}^i$ partonic cross section, calculable perturbatively

High energy limit



Large parameter

$$s \to \infty$$

Q^2 fixed, perturbative

High energy or Regge limit

$$s \gg Q^2 \gg \Lambda^2$$

Light cone proton momentum

$$p^+ = p^0 + p^z \qquad k_i^+ = x_i p^+$$

Strong ordering in longitudinal momenta

$$x \ll x_1 \ll x_2 \ll \cdots \ll x_n$$

Perturbative coupling but large logarithm

$$\bar{\alpha}_s \ll 1 \qquad \ln \frac{1}{x} \simeq \ln \frac{s}{Q^2} \gg 1$$

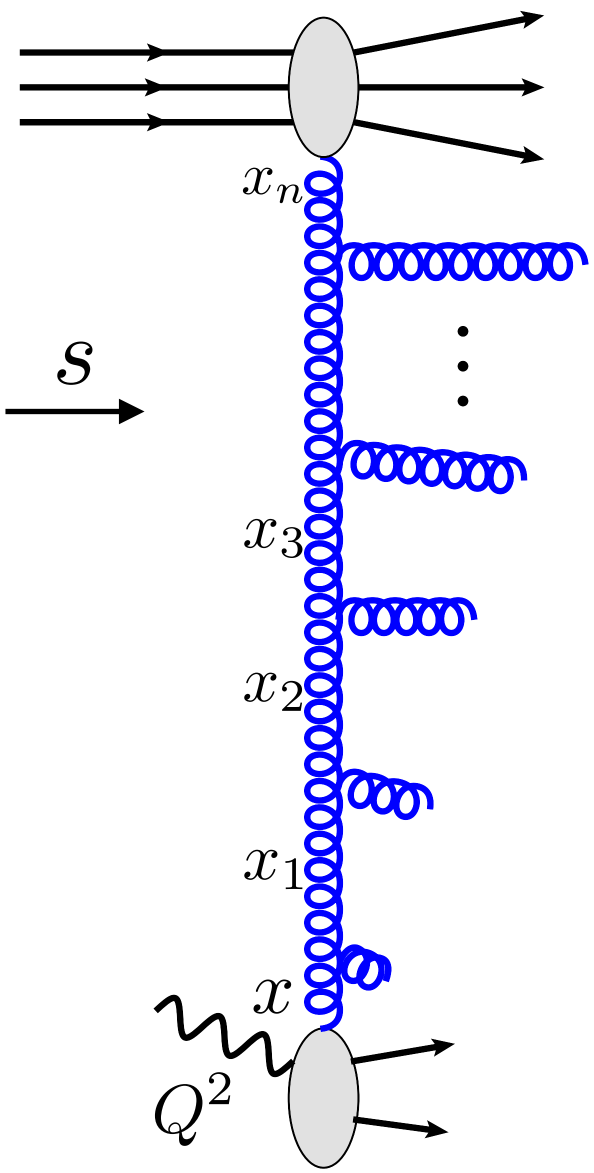
Large logarithms

$$\frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dz}{z} = \frac{\alpha_s N_c}{\pi} \ln \frac{1}{x} = \bar{\alpha}_s \ln \frac{1}{x}$$

Leading logarithmic resummation

$$\left(\bar{\alpha}_s \ln \frac{1}{x}\right)^n \qquad \left(\bar{\alpha}_s \ln \frac{s}{s_0}\right)^n$$

High energy limit



compare with DGLAP-collinear approach

Resummation performed by Bethe-Salpeter type equation
BFKL evolution equation

$$\frac{\partial \mathcal{F}_g(x,k_T)}{\partial \ln 1/x} = \int d^2k'_T\,\mathcal{K}(k_T,k'_T)\,\mathcal{F}_g(x,k'_T)$$

Branching kernel (perturbative expansion)

$$\mathcal{K} = \bar{\alpha}_s\mathcal{K}^{LLx} + \bar{\alpha}_s^2\mathcal{K}^{NLLx} + \bar{\alpha}_s^3\mathcal{K}^{NNLLx} + \ldots$$

QCD N=4 SYM

Unintegrated, (transverse momentum dependent) gluon density $\mathcal{F}_g(x,k_T)$

$$\frac{\partial f_i(x,Q^2)}{\partial \log(Q^2)} = \sum_j \int_x^1 \frac{dz}{z} P_{j\to i}(z) f_j(\frac{x}{z},Q^2)$$

Resummation

- Problems with convergence of small x expansion: NLL terms large
- Resummation need to be performed:
- Combining DGLAP and BFKL
- Kinematical constraints, momentum sum rule

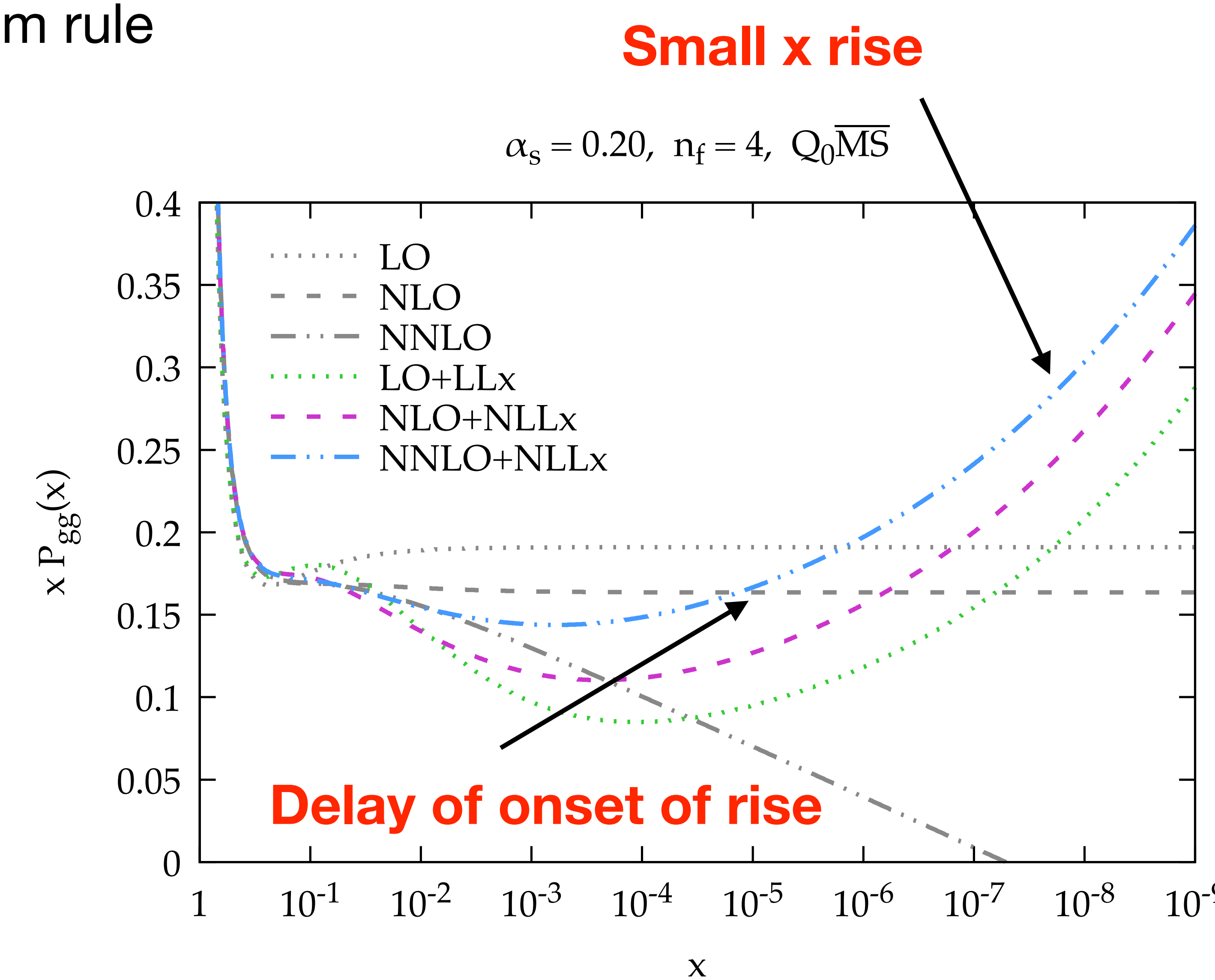
Altarelli, Ball, Forte
Kwiecinski
Ciafaloni, Colferai, Salam, AS
Thorne, White; Sabio-Vera

DGLAP will fail at small x , at some point. Question is when exactly?

Splitting function: NNLO has large negative term which dominates at small x.

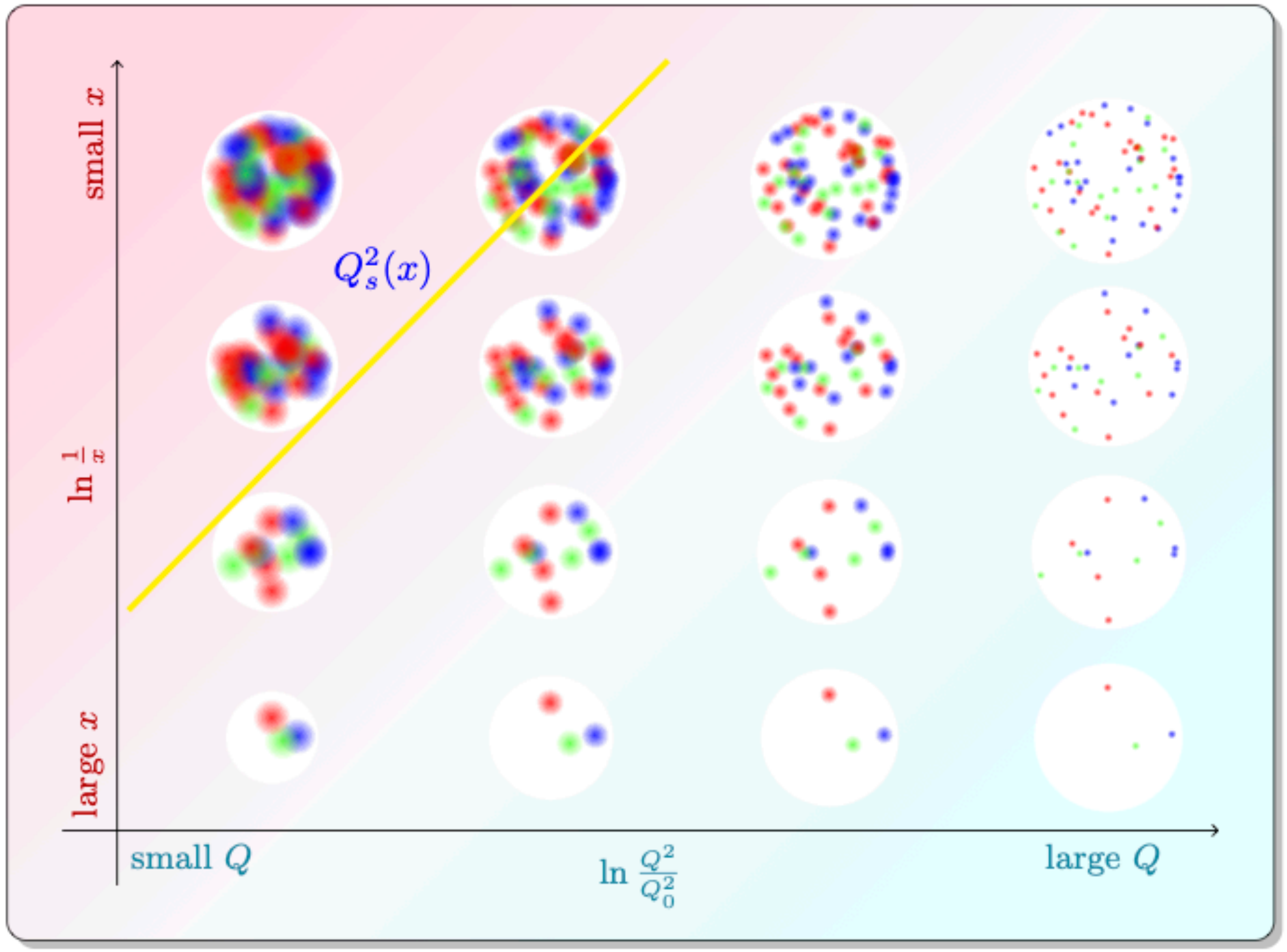
Resummation stabilizes the result

Improves the description of the F2 data



Ball,Bertoni,Bonvini,Marzani,Rojo,Rottoli

Parton saturation



At small x another effect possible: gluon saturation

High gluon density can lead to increase of recombination effects. Unitarity.

QCD at high energy : dynamically generated saturation scale

DGLAP+BFKL+saturation : example

Kutak,Sapeta; based on model by Kwiecinski, Martin,AS

$$\phi_p(x,k^2) \; = \; \phi_p^{(0)}(x,k^2)$$

BFKL+kinematical constraint

$$+ \frac{\alpha_s(k^2)N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_0^2}^\infty \frac{dl^2}{l^2}\left\{\frac{l^2\phi_p(\frac{x}{z},l^2)\,\theta(\frac{k^2}{z}-l^2) \; - \; k^2\phi_p(\frac{x}{z},k^2)}{|l^2-k^2|} + \frac{k^2\phi_p(\frac{x}{z},k^2)}{|4l^4+k^4|^{\frac{1}{2}}}\right\}$$

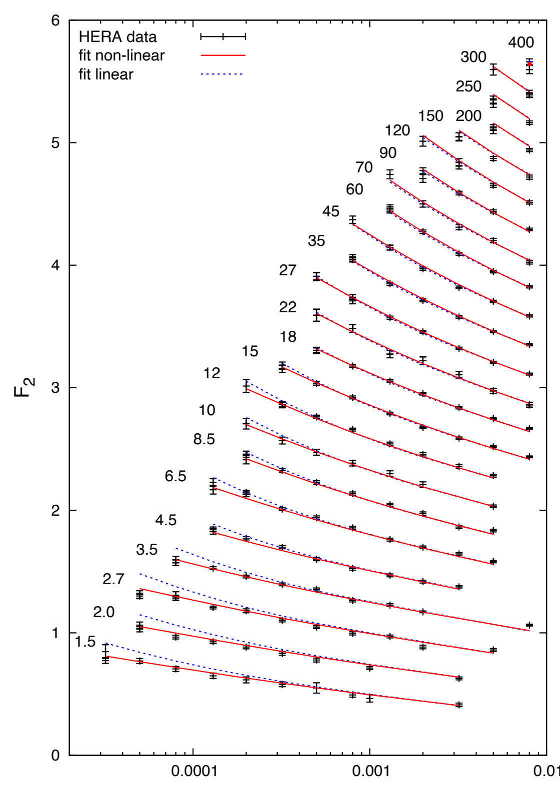
DGLAP splitting function (nonsingular part)

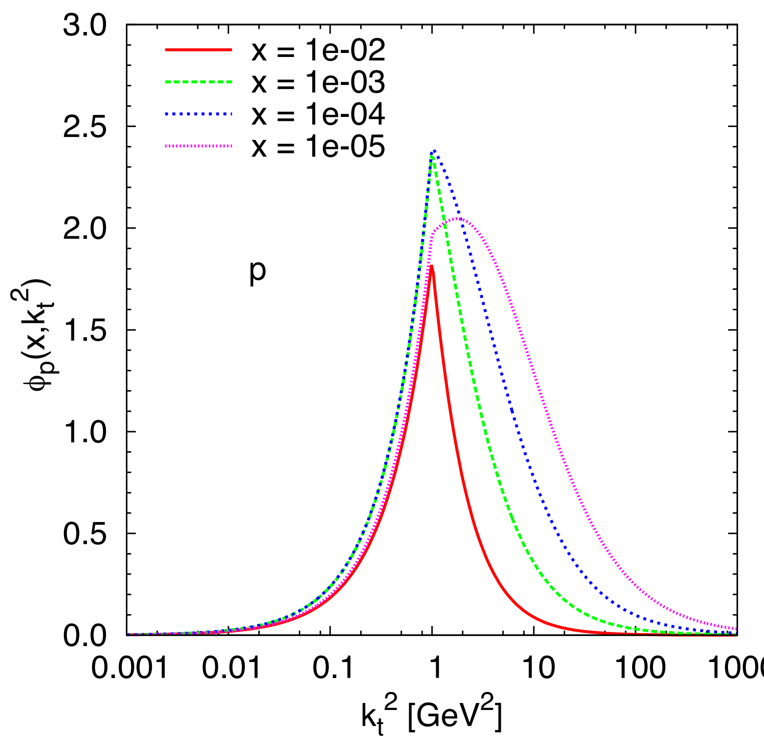
$$+ \frac{\alpha_s(k^2)}{2\pi k^2}\int_x^1 dz\left[\left(P_{gg}(z)-\frac{2N_c}{z}\right)\int_{k_0^2}^{k^2} dl^2\,\phi_p\left(\frac{x}{z},l^2\right) + zP_{gq}(z)\Sigma\left(\frac{x}{z},k^2\right)\right]$$

Nonlinear term

$$- \frac{2\alpha_s^2(k^2)}{R^2}\left[\left(\int_{k^2}^\infty \frac{dl^2}{l^2}\phi_p(x,l^2)\right)^2 + \phi_p(x,k^2)\int_{k^2}^\infty \frac{dl^2}{l^2}\ln\left(\frac{l^2}{k^2}\right)\phi_p(x,l^2)\right] ,$$

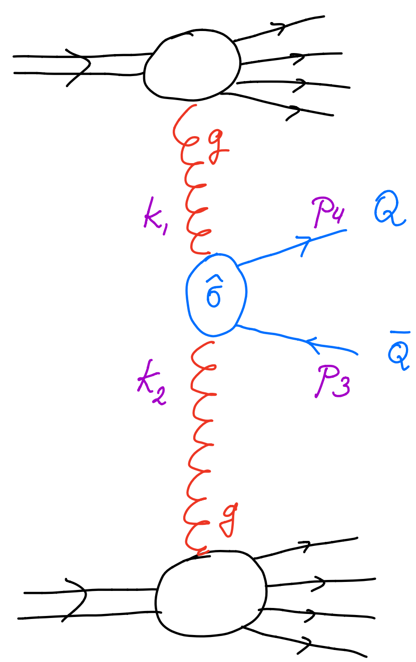
Good description of the data on F2





k_T factorization for heavy quark production

Catani,Ciafaloni,Hautmann;
Collins,Ellis



$$k_1 = (p_1^+, 0, \mathbf{k}_{1T}) \qquad p_1^+ = x_1 P^+$$

$$k_2 = (0, p_2^-, \mathbf{k}_{2T}) \qquad p_2^- = x_2 \tilde{P}^-$$

$$p_1^+ p_2^- = x_1 x_2 s$$

Off-shell gluons

$$k_1^2 = -\mathbf{k}_{1T}^2$$
$$k_2^2 = -\mathbf{k}_{2T}^2$$

Unintegrated gluon density

$$\sigma(m^2, s) = \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} \int d^2 k_{1T} F(x_1, \mathbf{k}_{1T}) \int d^2 k_{2T} F(x_2, \mathbf{k}_{2T})\, \hat{\sigma}(x_1, x_2, \mathbf{k}_{1T}, \mathbf{k}_{2T}, m)$$

Off-shell xsection

Forward region:

$$x_1 \gg x_2$$

Take hybrid (on-shell — off-shell) approach:

$$k_{1T} \to 0, k_{2T} \neq 0 \qquad k_1 = (p_1^+, 0, 0)$$

$$\sigma(m^2, s) = \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2}\, xg(x_1, \mu^2) \int d^2 k_{2T} F(x_2, \mathbf{k}_{2T})\, \hat{\sigma}(x_1, x_2, \mathbf{k}_{1T} \to 0, \mathbf{k}_{2T}, m)$$

Collinear gluon density

Setup

k_T factorization (based on Catani-Ciafaloni-Hautmann formula) for charm with unintegrated gluon from Kutak-Sapeta (the same formalism used previously (*BEJKRSS*) for evaluation of prompt neutrino flux in IceCube ; other models for unintegrated gluon still to be considered)

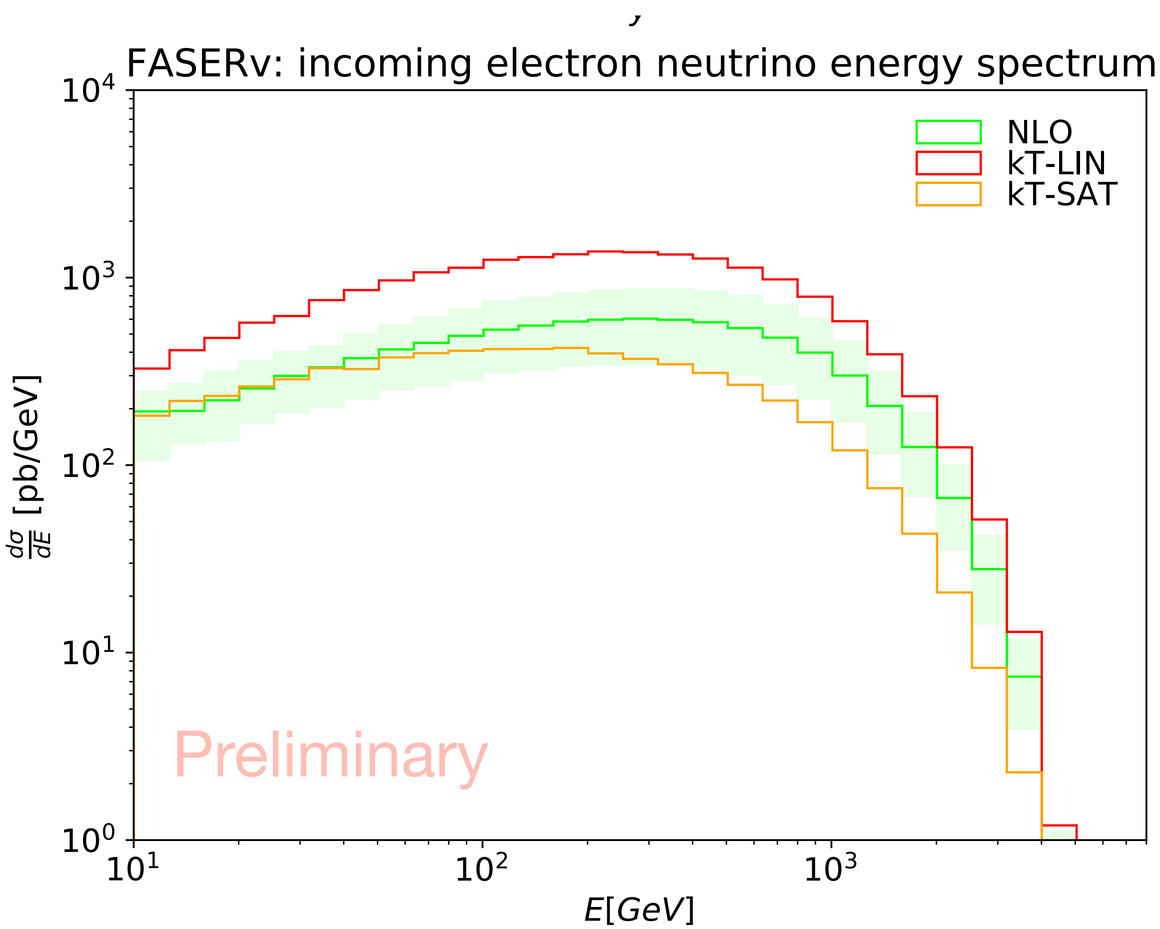
Different fragmentation scenarios tested for D mesons: ex. Peterson function vs PYTHIA

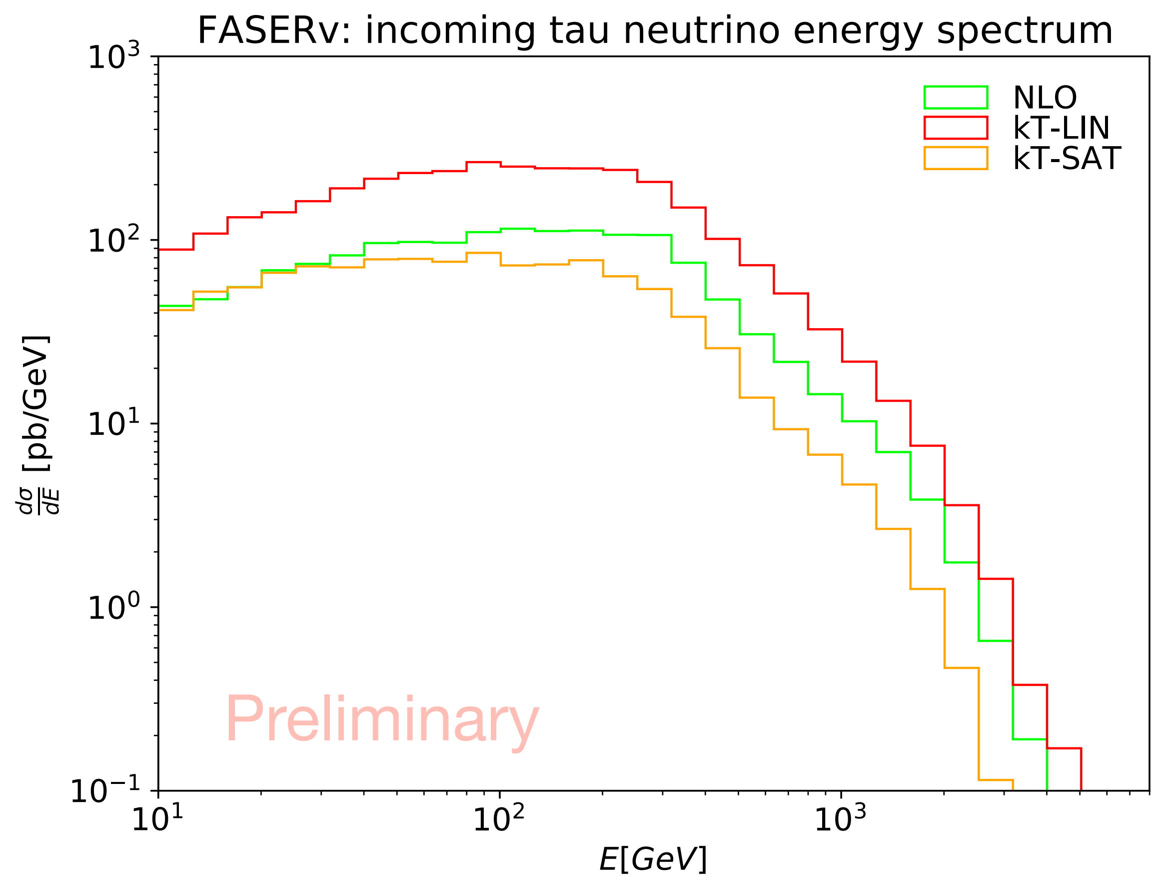
Compare with NLO and MC generators and cross check with collider data on D mesons

Compute neutrino flux at FASERnu

Note : all the results are preliminary.

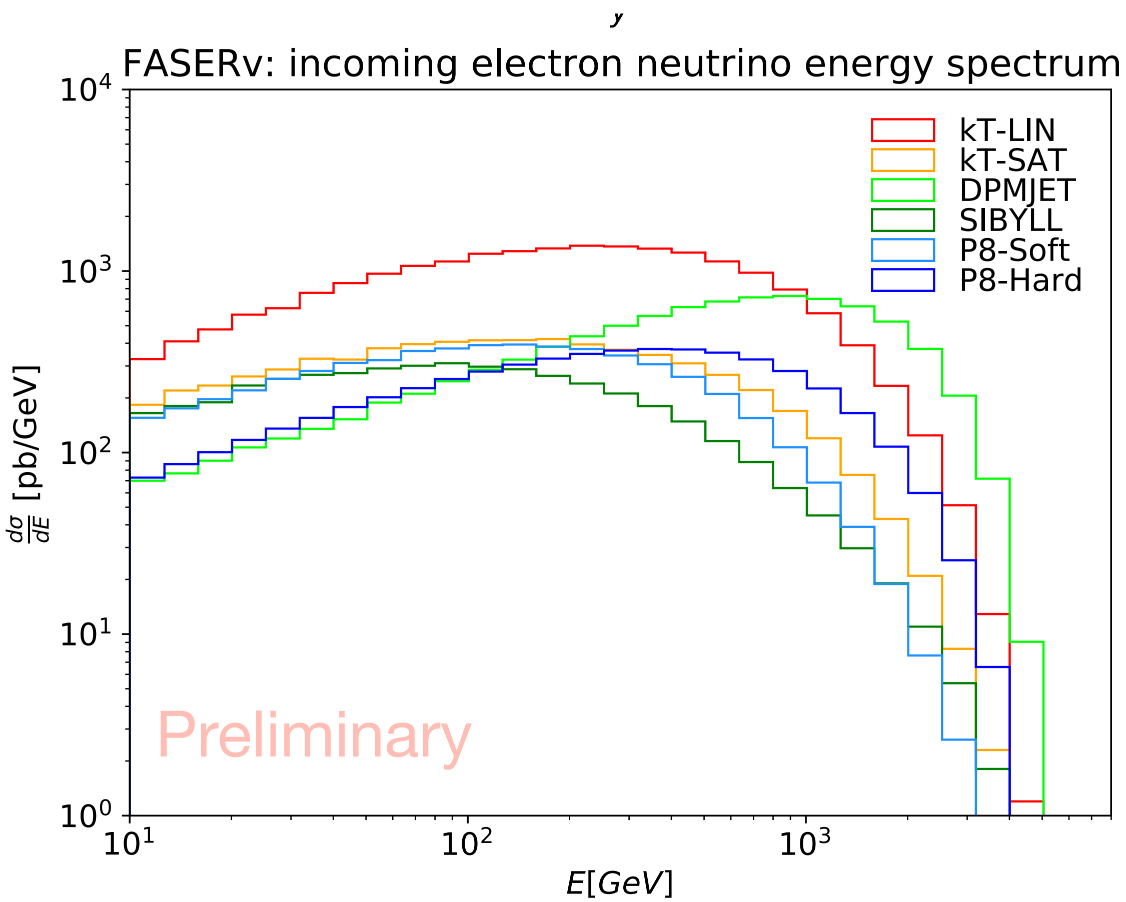
Neutrino spectrum

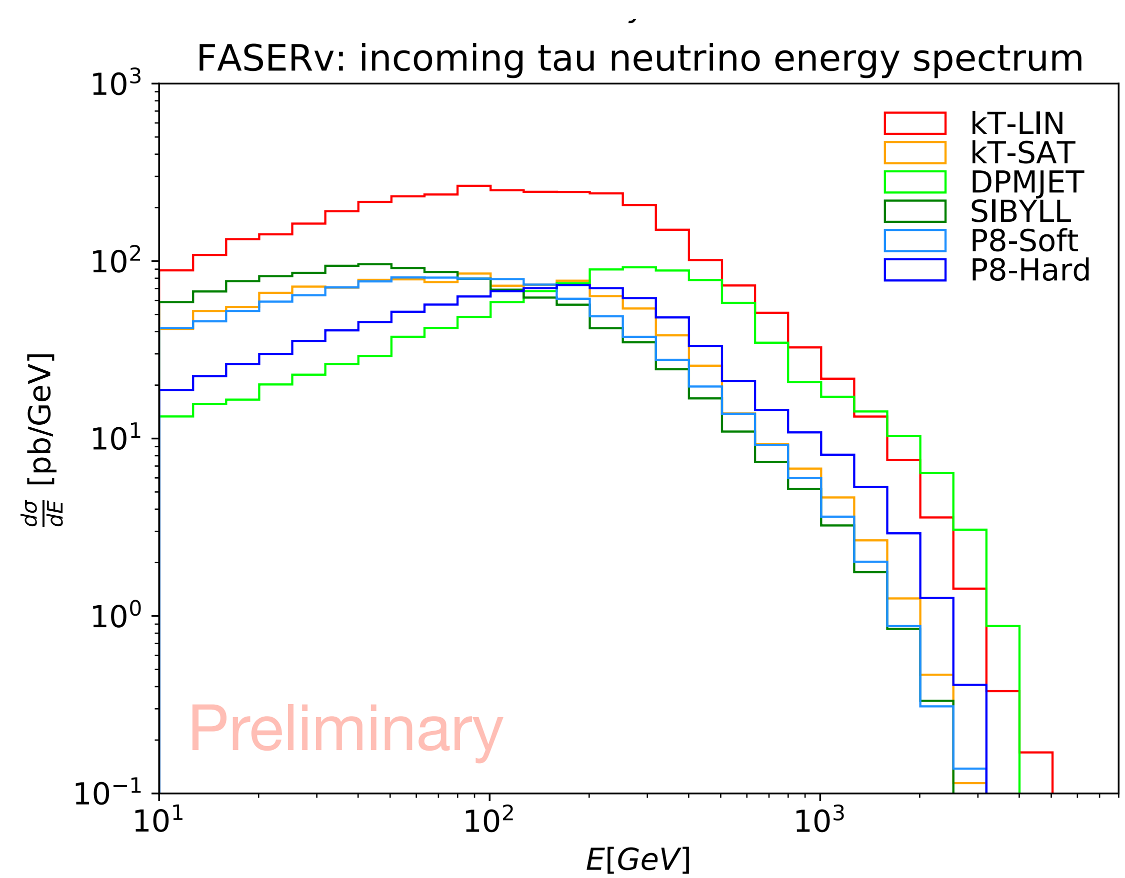




Range of uncertainties for the NLO scale variation of the same order as the small x calculation i.e. difference between linear and nonlinear (in the forward region)

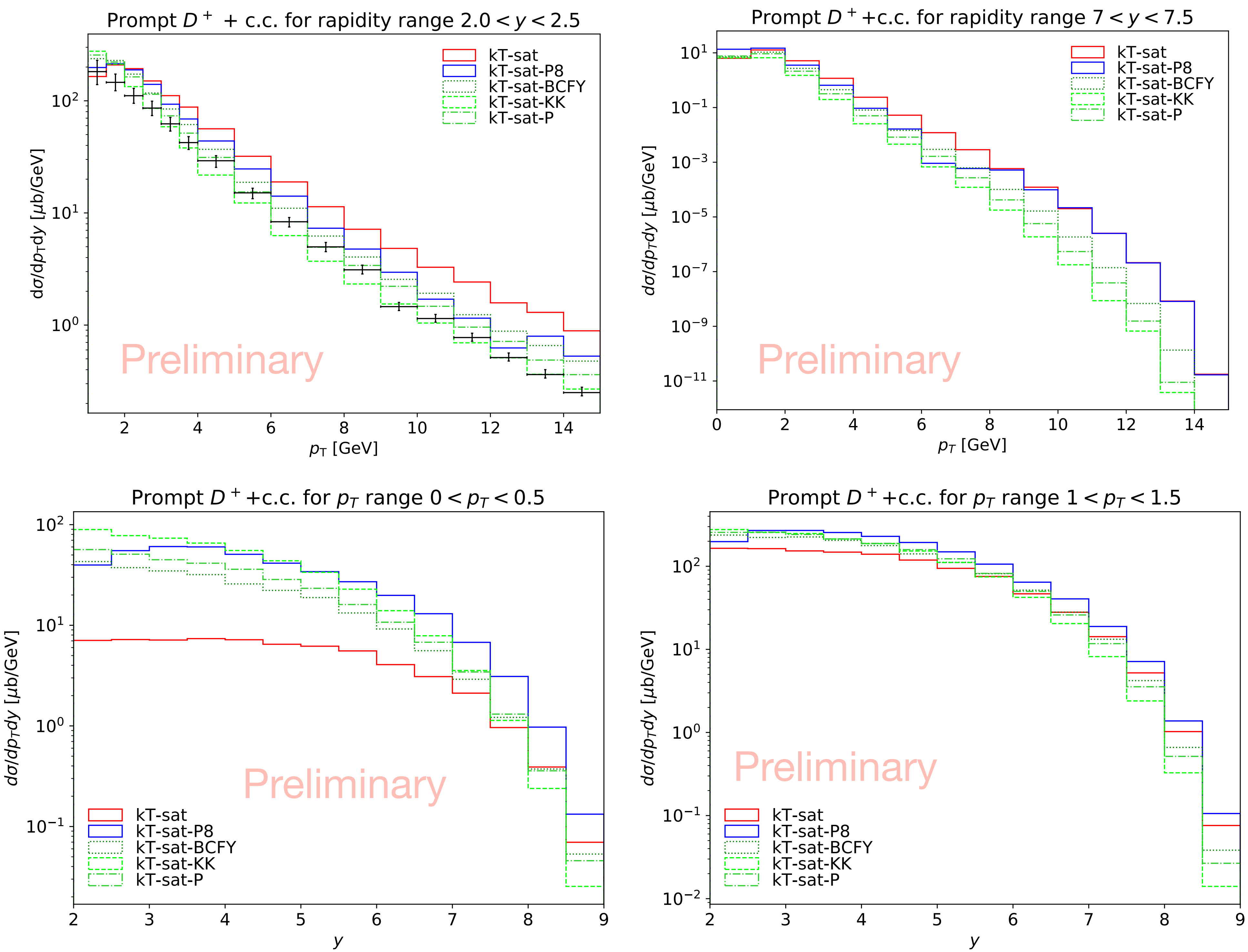
Neutrino spectrum



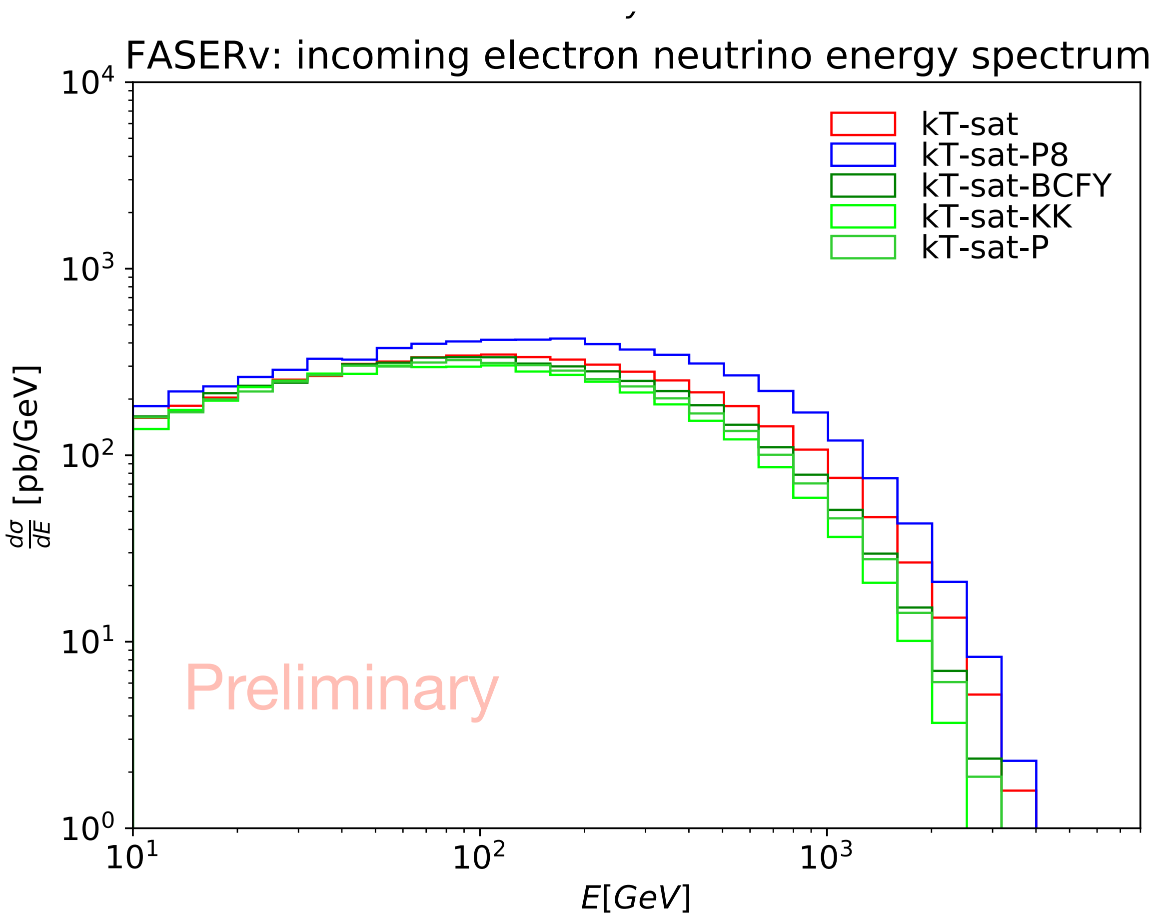


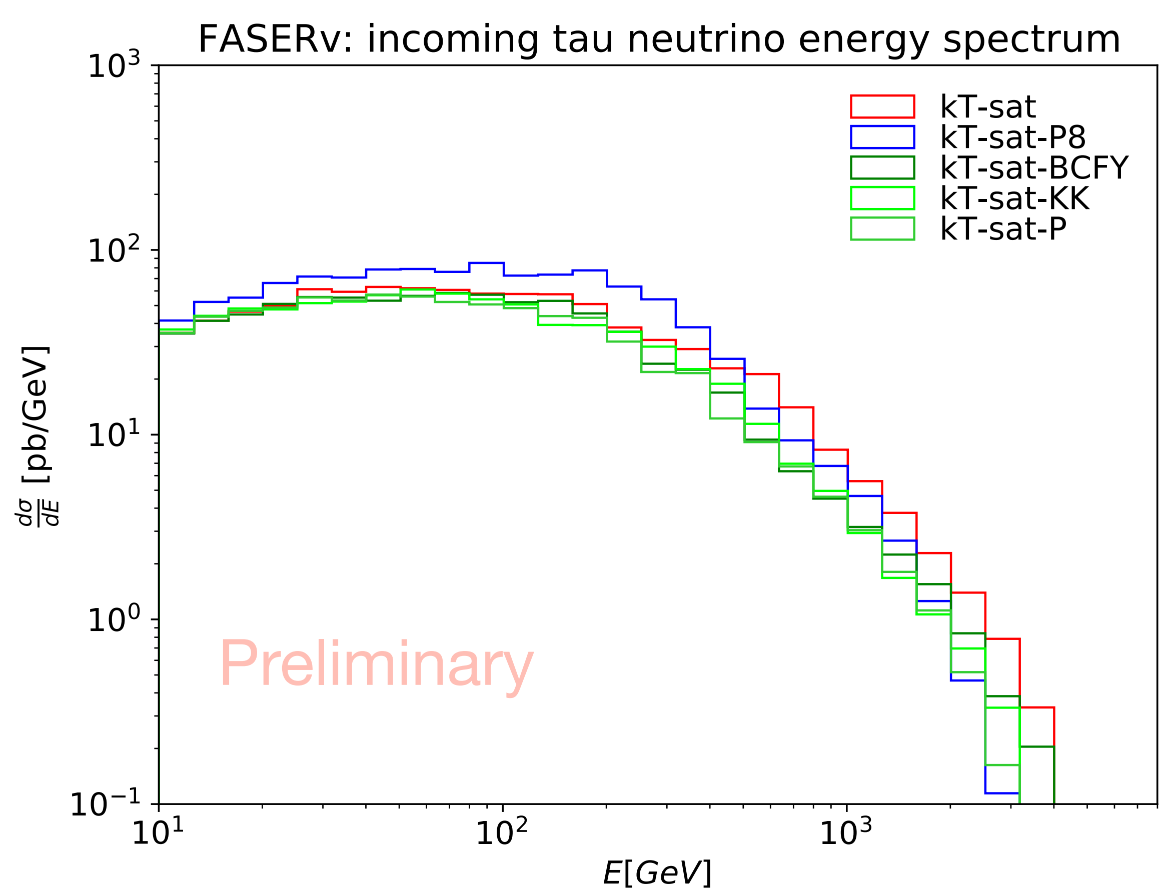
Significant differences in the energy spectrum from different generators

Impact of fragmentation



Impact of fragmentation





Significant differences in the energy spectrum due to the fragmentation
Does factorization hold for fragmentation in the very forward region ??

Summary

- With increasing energies small x resummation becomes necessary
- FASER sensitive to very forward region in particle production
- Small x dynamics important: differences between linear and non-linear scenarios large.
- Sensitivity to fragmentation scenarios: is standard fragmentation applicable in the forward region in hadron-hadron collision environment ? Applicability of standard factorization?