Neutrino fluxes at the FPF: the case of ν_τ

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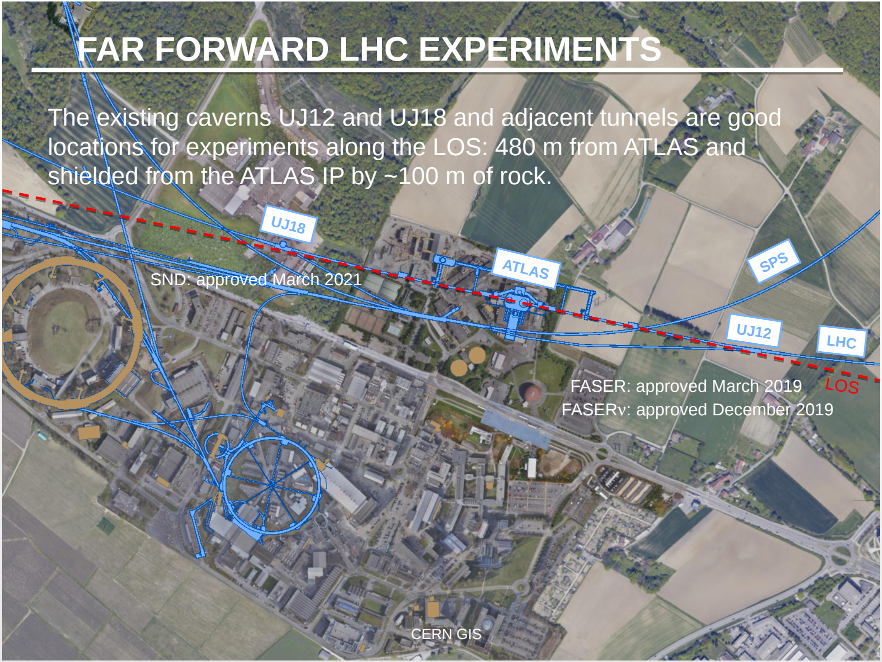
PROSA – proton structure analyses in hadronic collisions

mainly on the basis of [arXiv:2002.03012] + updates

2nd Forward Physics Facility Meeting, zoom, May 27th - 28, 2021

FAR FORWARD LHC EXPERIMENTS

The existing caverns UJ12 and UJ18 and adjacent tunnels are good locations for experiments along the LOS: 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock.



Far-forward LHC experiments and ν fluxes

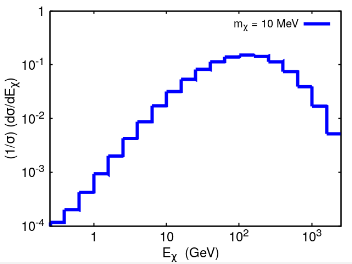
* FASER, FASERν and SND@LHC are all going to take data during LHC Run 3.
* They will measure "events" from the **convolution** of **fluxes (production + propagation)** and **interaction** σ with target.
* Are we able to disentangle these elements from the experimental point of view ?
* Predictions for ν fluxes wanted !

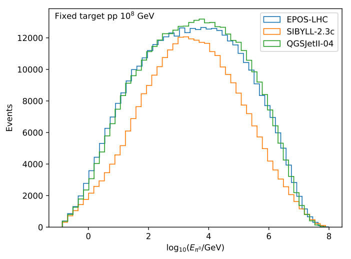
- if we want to use interaction cross-sections for a sound nPDF program
- if we want to measure $\nu_a \to \nu_s$ oscillation mixing parameters
- if we want to disentangle BSM signals from SM background (e.g. heavy-neutral lepton mixing, hidden-sector DM)
- etc....

* In the following we focus on ν_τ: why ?

- It is the "easiest" from the (p)QCD point of view.
- It is interesting from the physics point of view: only a few ν_τ have been identified so far in experiments around the world
  $\Rightarrow$ Lepton Universality probes needed.....

Not only ν but even BSM fluxes wanted!





plot by S. Trojanowsky *last-minute plot by J. Manshanden*
FLaRE geometry, CM frame *inclusive, CR LAB frame*

∗ Example: hidden sector DM coupled to the SM through a dark photon A' with $m_\chi < m_{A'} << m_{EW}$.

∗ A' produced either by $pp \to ppA'$ (proton bremsstrahlung) or through $pp \to \pi^0, \eta, ... + X \to A'\gamma + X$

from B. Batell et al. [arXiv:2101.10338]

∗ How reliable/uncertain are BSM particle fluxes ?

∗ Somehow similar issues as for the determination of ν fluxes!

Neutrino fluxes

* neutrino flux from light-flavour decay:

$$pp \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + \mathrm{X} \rightarrow \pi^{\pm}, K^{\pm} + \mathrm{X} \rightarrow \nu_\ell(\bar{\nu}_\ell) + \ell^{\pm} + \mathrm{X},$$
$$pp \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + \mathrm{X} \rightarrow K_S^0,\, K_L^0 + \mathrm{X} \rightarrow \pi^{\pm} + \ell^{\mp} + \nu_\ell + \mathrm{X}$$
$$pp \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + \mathrm{X} \rightarrow \textit{light-hadron} + \mathrm{X}' \rightarrow \nu(\bar{\nu}) + X'' + X'$$

* neutrino flux from heavy-flavour decay:

$$pp \rightarrow c, b, \bar{c}, \bar{b} + \mathrm{X} \rightarrow \textit{heavy-hadron} + \mathrm{X}' \rightarrow \nu(\bar{\nu}) + X'' + X'$$

where the decay to neutrino occurs through semileptonic and leptonic decays:
e.g. $D^+ \rightarrow e^+ \nu_e X$, $D^+ \rightarrow \mu^+ \nu_\mu X$,
$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm}$, with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \mathrm{X}$

$c\tau_{0,\,\pi^{\pm}} = 780$ cm, $c\tau_{0,\,K^{\pm}} = 371$ cm, $c\tau_{0,\,D^{\pm}} = 0.031$ cm

N.B. other channels of neutrino production occur in the Standard Model,
e.g. W boson and t quark production and leptonic decay,
but suppressed far-forward with respect to the previous channels.

* In our work we focus especially on neutrino fluxes from heavy-flavour:
$\nu_\tau + \bar{\nu}_\tau$ are mainly produced through this channel.

Light flavour vs. heavy flavour

$*$ Light-flavoured hadrons include only light quarks as valence quarks in their composition.

$* \; m_u, \;\; m_d, \;\; m_s << \Lambda_{QCD}$

$\Rightarrow \alpha_S(m_u), \;\; \alpha_S(m_d), \;\; \alpha_S(m_s) \;\; > 1$

$\Rightarrow$ Light hadron production at low p_T is dominated by non-perturbative QCD effects.

$*$ Heavy-flavoured hadrons include at least one heavy-quark as valence quark in their composition.

$* \; m_c, \;\; m_b >> \Lambda_{QCD}$

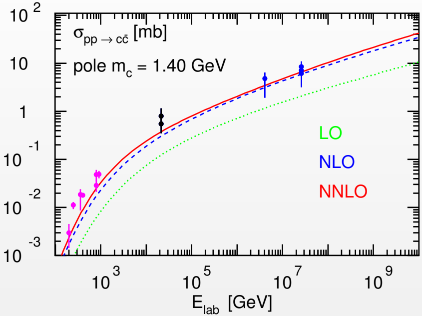
$\Rightarrow \alpha_S(m_c), \;\; \alpha_S(m_b), \;\; << 1$

$\Rightarrow$ At a scale $\sim m_Q$, QCD is still perturbative. Charm is produced perturbatively (if one neglects possible intrinsic charm contributions from PDFs) even at low p_T, but non-perturbative effects at such low scales may also play important roles.

$* \; m_c, \;\; m_b <<$ present collider energies

$\Rightarrow$ Multiscale issues, appearence of large logs.

$\sigma(pp \to c\bar{c}(+X))$ at LO, NLO, NNLO QCD



$(E_{lab} = 10^6 \text{ GeV} \sim E_{cm} = 1.37 \text{ TeV})$
$(E_{lab} = 10^8 \text{ GeV} \sim E_{cm} = 13.7 \text{ TeV})$
$(E_{lab} = 10^{10} \text{ GeV} \sim E_{cm} = 137 \text{ TeV})$

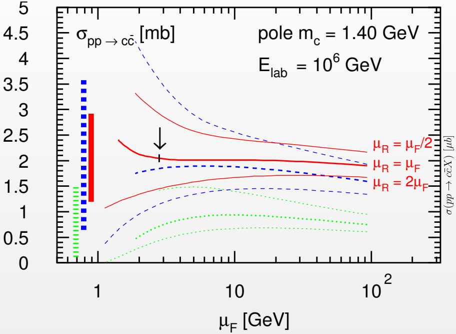
data from fixed target exp (E769, LEBC-EHS, LEBC-MPS, HERA-B)
+ colliders (STAR, PHENIX, ALICE, ATLAS, LHCb).

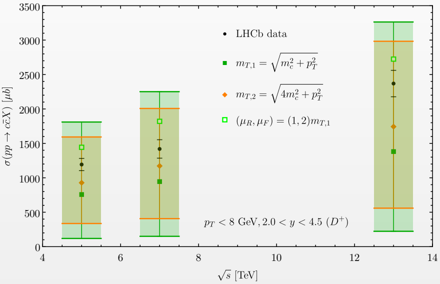
$*$ Assumption: collinear factorization valid on the whole energy range.

$*$ Sizable QCD uncertainty bands not included in the figure.

$*$ Leading order is not accurate enough for this process:
at NLO new channels open, due to qg interactions.

Inclusive charm production: scale choices and theory predictions vs. LHCb experimental data





- ∗ Sensitivity to radiative corrections is smaller at a scale $\mu_R \sim \mu_F \sim 2m_c$ than at the scale $\mu_R \sim \mu_F \sim m_c$.
- ∗ This translates into a dynamical scale $\sqrt{p_{T,c}^2 + 4m_c^2}$ to better catch dynamics in differential distributions.
- ∗ Comparison with LHCb exp. data consistent with these observations.

From parton production to heavy-flavour hadrons

Different descriptions of the transition are possible:

1) Convolution of cross-sections with Fragmentation Functions

2) Fixed-order QCD + Parton Shower + hadronization:
match the fixed-order calculation with a parton-shower algorithm (resummation of part of the logarithms related to soft and collinear emissions on top of the hard-scattering process), followed by hadronization (phenomenological model).

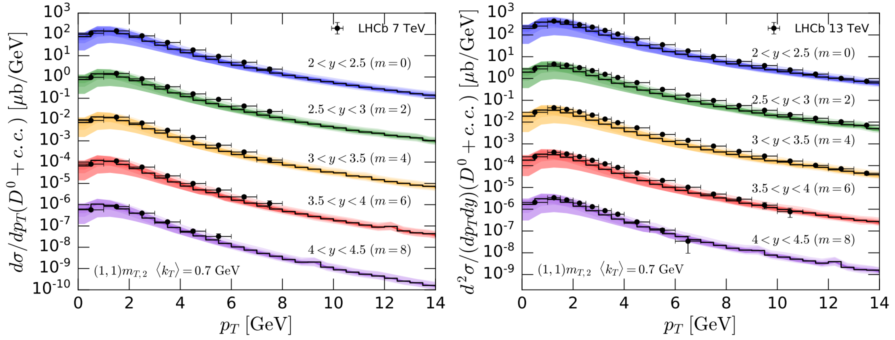
Advantage: fully exclusive event generation, correlations between final state particles/hadrons are kept.

Problem: accuracy not exactly known.

Both methods 1) and 2) used here.

In both cases, additional non-perturbative contribution due to intrinsic $\langle k_T \rangle$, related to the confinement of the initial state partons into hadrons, is added.

$D_0 + \bar{D}_0$ production: theory predictions vs. LHCb experimental data



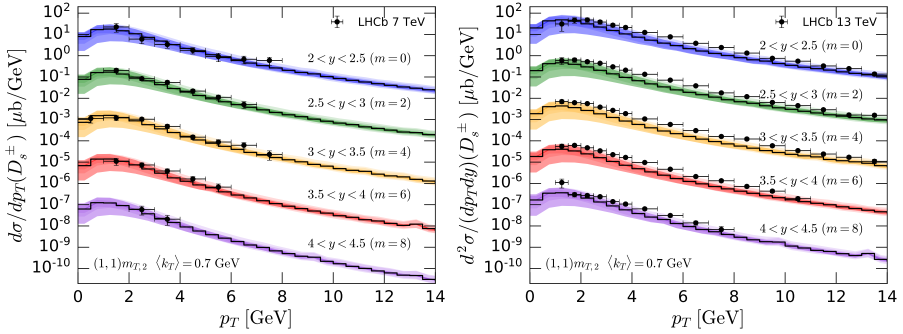
$\sqrt{s} = 7$ TeV $\qquad$ $\sqrt{s} = 13$ TeV

∗ p_T distributions in different rapidity bins are considered.

∗ Experimental data have uncertainty bands much smaller than theory predictions.

∗ Similarly good agreement theory/experiment in low p_T bins at all LHCb rapidities.

$D_s + \bar{D}_s$ production: theory predictions vs. LHCb experimental data



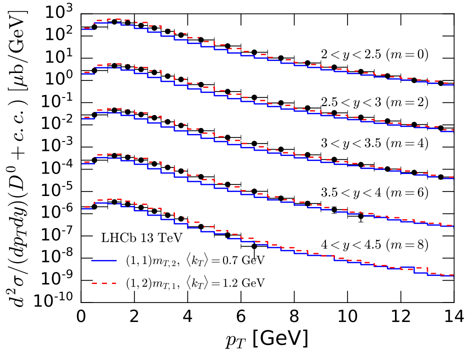
$\sqrt{s} = 7$ TeV $\sqrt{s} = 13$ TeV

∗ p_T distributions in different rapidity bins are considered.

∗ Experimental data have uncertainty bands much smaller than theory predictions.

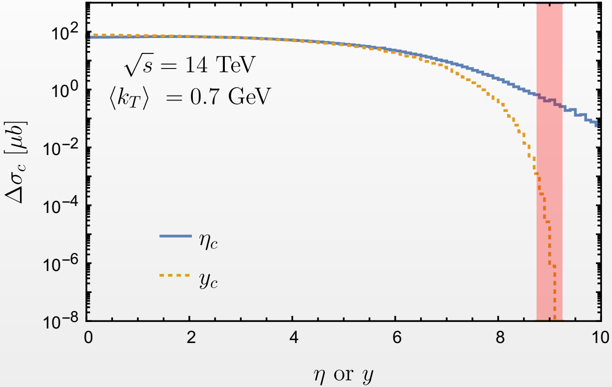
∗ Less precise exp. data. D_s data at low p_T are missing!

And if we try to fit the LHCb experimental data ?



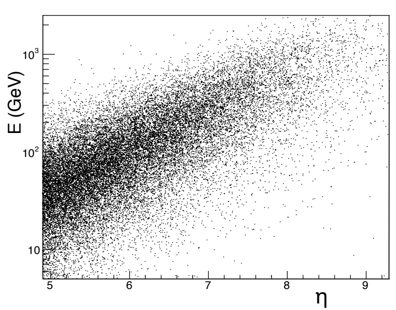
- ∗ Dangerous operation: the experimental data may be wrong!
- ∗ The "best fit" configuration turns out to correspond to other scales (less justified from the theory point of view) + intrinsic $\langle k_T \rangle > 1$ GeV.
- ∗ This shows that there are other QCD effects that can be approximately reabsorbed in a change of scale an into an (intrinsic) $\langle k_T \rangle$ smearing model, which play a role in this process.
- ∗ Part of these effects are expected to be of perturbative origin and another part of non-perturbative origin.

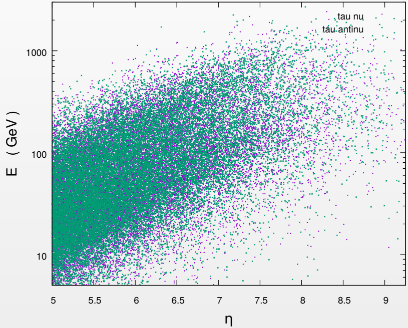
Charm production at large rapidity/pseudorapidity



* For forward charm production ($\eta_c \gtrsim 6$) rapidity and pseudorapidity distributions increasingly differ.
* η_ν distribution effectively limited by the fact that y_c distribution is bounded.

Scatter-plots in (η, E) for heavy-flavour ν and $\bar{\nu}$ production

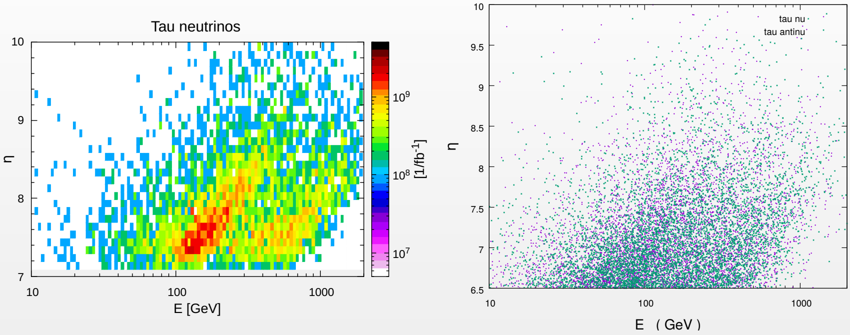




PYTHIA in [arXiv:2004.07821] vs. NLO QCD + PYTHIA

* More energetic neutrinos at higher rapidities.

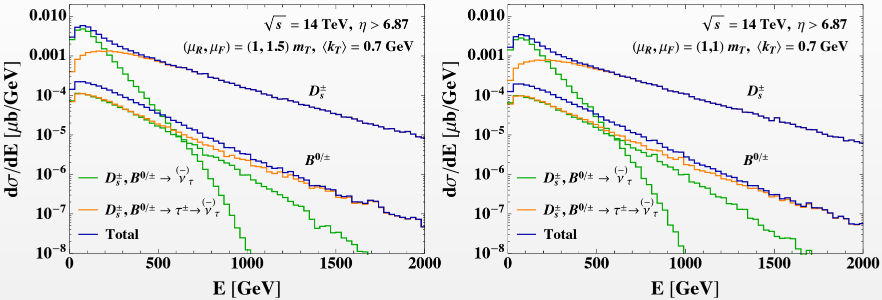
Scatter-plots in (E, η) for ν_τ and $\bar{\nu}_\tau$ production



DPMJET/FLUKA in [arXiv:2004.07821] vs. NLO QCD + PYTHIA

* Can we distinguish ν_τ from direct $D_s \to \nu_\tau$ decay from those from chain $D_s \to \tau \to \nu_\tau$ decay ?

Energy distribution of forward $\nu_\tau + \bar{\nu}_\tau$



from W. Bai et al. [arXiv:2002.03012]

∗ direct decay and chain decay contribute to the total in different energy regions

∗ contributions from *B* meson decays are one-two order of magnitude smaller than those from *D* mesons.

∗ What are the dominant uncertainties on these distributions ?

Geometry for forward neutrino detection considered in our work

* A 35.6 ton Pb detector of $R = 1.0$ m and length $\ell = 1$ m at $D = 480$ m from the pp interaction point, corresponding to $\eta > 6.87$.
* LHC integrated luminosity $\mathcal{L} = 3000$ fb^{-1}
* The point of production of tau neutrinos and taus from $D_s^\pm$ has distance $d = \gamma c \tau_{D_s} \sim E_{D_s}/m_{D_s} \cdot 150\ \mu$m ~ 1.5 - 15 cm for $E_{D_s} = 200$ GeV - 2 TeV.
* Similarly for tau neutrinos from $B^\pm$, $d = \gamma c \tau_{B^\pm} \sim E_{B^\pm}/m_{B^\pm} \cdot 496\ \mu$m ~ 1.9 - 19 cm for $E_{D_s} = 200$ GeV - 2 TeV.
* And for neutrinos from τ decay, $d' = \gamma c \tau_\tau = E_\tau/m_\tau \cdot 87.11\ \mu$m ~ 0.98 - 9.8 cm.

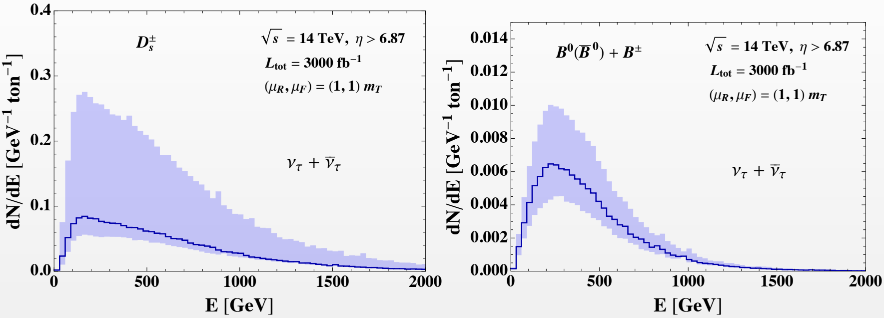
Total number of CC ($\nu_\tau + \bar{\nu}_\tau$) events

	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$				
$(\mu_R,\ \mu_F)$	$(1,\ 1)\ m_T$			$(1,\ 1)\ m_T$			$(0.5,\ 1)\ m_T$	$(1,\ 0.5)\ m_T$
$\langle k_T \rangle$	0.7 GeV			0 GeV	1.4 GeV	2.2 GeV	0.7 GeV	
D_s	1591	774	2365	2455	2143	1822	7834	1179
$B^{\pm,0}$	87	42	129	131	124	115	202	91
Total	1678	816	**2494**	2586	2267	1937	**8036**	**1870**

Table : The charged-current event numbers for tau neutrinos and antineutrinos in 1 m length of the lead detector (equivalent to $M_{\rm Pb} \simeq 35.6$ ton) assuming central scales $(\mu_R, \mu_F) = (1.0, 1.0)\, m_T$ in the computation of heavy-meson production in pp collisions at $\sqrt{s} = 14$ TeV and an integrated luminosity $\mathcal{L} = 3000$ fb^{-1}.

$\Rightarrow$ Estimate to be repeated with updated scale + PDF choice

Energy distribution of CC $(\nu_\tau + \bar{\nu}_\tau)$ events



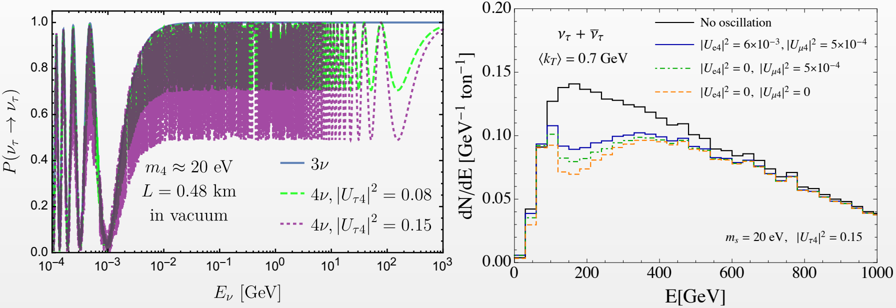
* The huge uncertainty band is due to (μ_R, μ_F) scale uncertainties.

* It means that higher-order pQCD contributions are probably large.

* In case of bottom production, scale uncertainty is smaller (+60%, -30%) than for charm (+250%, -30%) in relation to the fact that $m_b > m_c \Rightarrow \alpha_S(\mu_R = m_b) < \alpha_S(\mu_R = m_c)$.

$\Rightarrow$ Estimate to be repeated with updated scale + PDF choice

Other physics opportunities with ν_τ (complications for HNL searches): ν oscillations



from W. Bai et al. [arXiv:2002.03012]

∗ For the baseline and the neutrino energy range of the Forward Physics Facility, oscillations between active neutrinos in the SM are suppressed.

∗ Oscillation of ν_τ in heavy sterile neutrinos ($m_4 \sim 20$ eV) can be probed, by looking at deficit or excess in the observed event spectrum.

Conclusions

* The present QCD uncertainties on the $(\nu_\tau + \bar{\nu}_\tau)$ flux are large.

* An experimental measurement of this flux would be interesting not only for the study of neutrino oscillation effects, but even for constraining theoretical QCD aspects relevant to charm and bottom production and decay at hadron colliders.

* In particular we need a better understanding of the entity of non-perturbative vs. perturbative contributions. The charm mass is large enough with respect to Λ_{QCD} to allow the application of pQCD methods down to $p_T \to 0$. However, in this regime non perturbative QCD effects also play a relevant role, that needs to be better quantified.

* Understanding this point, on the other hand, may have effects on fits of Parton Distribution Functions and Fragmentation Functions, which, in turn, are ingredients of even other calculations.

* The larger is the η probed by an experiment, the most uncertain is our present theoretical knowledge.