QCD at the Forward Physics Facility @ CERN

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The Forward Physics Facility @ CERN

- Exploit beams of particles produced in the interactions points at the LHC, propagating in the direction tangent to the beam line.
- Let the beam propagating for some distance, until they interact with the material of one or more detectors.

Questions:
- at which angle positioning the detector(s) ? ($6 \lesssim \eta \lesssim 10$)
- how far from the IP ? ($\sim 500$ m near ATLAS IP or less near CMS IP)
- which detection technology and materials ?
- besides exploiting $pp$ HL-LHC runs, shall one consider $pA$ and $AA$ runs ?

⇒ The answers partly depend on the physics one wants to explore, partly on the morphology of the experimental environment.

Experience built on top of experiments active during Run-3 will help (Faser-$\nu$, FASER....).
Characterizing the beam

* At distance far enough from the interaction point, after optical elements, the beam is composed by neutrinos and muons.

* Neutrinos come mainly from the decays of various mesons and baryons (light-flavoured and heavy-flavoured) produced at the IP.

* How to characterize the beam?

⇒ Predictions for the energy and angular spectra of the $\nu_e$, $\nu_\mu$, $\nu_\tau$ components, accompanied by uncertainties of perturbative and non-perturbative nature.

A-posteriori complication: $\nu$ could oscillate and disappear during propagation!
Examples of MC predictions of forward ($\nu + \bar{\nu}$) fluxes

Estimated number of neutrinos impinging on the transverse area of the FASER-$\nu$ detector.

Uncertainty band: envelope of the central predictions of different MC.

How to estimate a more reliable uncertainty band?
Non-perturbative effects potentially affecting predictions for $\nu$ beams at the FPF

* Modelling of PDFs (at various stages of the simulation)
* Modelling of MPI (partly perturbative)
* Modelling of hadronization (including color reconnection effects)
* Heavy-quark treatment/mass values/interpretation
* Factorization framework
* Modelling of diffraction

$\Rightarrow$ Models and tunes implemented in MC event generators
  + non-perturbative parameters in the hard-scattering

Long-standing issue: difficulties to simultaneously reproduce the experimental charged particle multiplicities (and other observables) at small and large pseudorapidities.
Parton Distribution Functions

* Forward $\nu$ production in $pp$ collisions implies sensitivity to PDFs in the regions $10^{-8} \lesssim x \lesssim 10^{-5}$ and $10^{-1} \lesssim x \lesssim 1$

* These are the regions where present PDF fits are less constrained!

* Partly constrained by LHCb heavy-flavour production data ($2 < y < 4.5$), but PDFs still extrapolated to the more extreme $x$ values.

Questions:

* Is the DGLAP formalism in collinear factorization appropriate enough to describe proton content at low $x$, low $Q^2$?

* How to model higher-twist effects?

* Do we need to switch to more general factorization and evolution frameworks including gluon saturation?

⇒ Partial overlap with $x$ regions explorable at EIC (large $x$) and LHeC (small $x$).
Recent results on gluon PDFs

* Comparison between NLO PDF fits incorporating or not LHCb open heavy flavour data (left).
* Effects of cuts of inclusive DIS data on the ABMP gluon distribution (right).
Multiple Partonic Interactions

* Interactions at lower $x$ with respect to the hard-scattering. Tame the divergences in perturbative $2 \rightarrow 2$ scatterings.

* Dual Parton Scattering often modelled with pocket formulas using $\sigma_{\text{eff}}$ parameter.

Questions:
- How to go beyond the present treatment?
- PDFs in MPI?
- rescattering (and non-trivial color flows) in MPI?
- how to implement color reconnection effects (many color strings overlapping in physical space)?
Hadronization

* String and cluster hadronization mechanisms available in Monte Carlo event generators.

* Color connections and reconnection effects.

* Questions:
  up to which extent is it meaningful to apply the results of fits of $e^+e^-$ data to $pp$ collisions (gluon jets/initial state hadrons) ?

⇒ Asymmetries in forward production of mesons with opposite charge may give hints on beam remnant effects in the hadronization mechanisms.
**Primordial \( k_T \)**

* Introduced in MC generators in collinear factorization, to account for Fermi motion of partons confined in the proton.

* Average \( \langle k_T \rangle \) value tuned to experimental data (Drell-Yan production at low \( p_T \)).

* The result may depend on the perturbative accuracy of the simulation: a large intrinsic \( \langle k_T \rangle \) can mimic missing higher-order perturbative effects!

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**Question:**

Is it enough to improve the accuracy of the computation in the collinear factorization framework (e.g. NNLO, better PDFs/FFs, etc...), or shall we go beyond collinear factorization?
Conclusions

* Characterizing and quantifying the non-perturbative uncertainties affecting forward $\nu$ beams is crucial to be able to use these beams for further SM and BSM studies (e.g. $\nu$ oscillations and nuclear PDF extraction from $\nu$-induced DIS in the detector).

* Measuring/inferring the beam composition at different angles and energies will allow for a better understanding of non-perturbative mechanisms.

* Open issue:
how to distinguish the relative role of different non-perturbative mechanisms? Modifying one element can compensate for the effect of other missing ones!

$\Rightarrow$ Importance of the synergy between different experiments.
Next discussion opportunities on the FPF

* Talks in the Snowmass CPM-meeting session #138
  “Synergy of Astroparticle and Collider Physics” tomorrow.

* FPF Kickoff Meeting, via zoom on November 9-10, 2020:

  https://indico.cern.ch/event/955956/overview

  • Registrations open.
  • Snowmass inter-frontier participation:
    SM/BSM/astroparticle and collider phenomenologists
  • Call for abstracts from these communities open until October, 25th.

⇒ Discussions and work in preparation of the Snowmass report
   and a practical proposal for the facility.

Thank you for your attention!