Far-forward Neutrinos (and Long-Lived Particles) at the LHC

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with input from W. Bai, M. Diwan, M.-H. Reno, Y. S. Jeong
+ many authors of the Snowmass 2021 FPF reports

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

PROSA
proton structure analyses in hadronic collisions

mainly on the basis of [arXiv:2002.03012[hep-ph]], [arXiv:2112.11605[hep-ph]], [arXiv:2203.07212[hep-ph]], [arXiv:2212.07865[hep-ph]], and the two FPF Snowmass 2021 reports [arXiv:2109.10905[hep-ph]], [arXiv:2203.05090[hep-ph]],

GGI Workshop “Theory challenges in the precision Era of the LHC”
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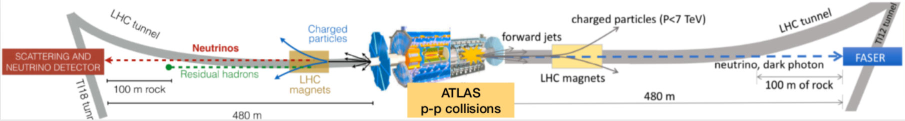
Far-forward LHC experiments

* Various projects to exploit beams of particles produced in the interactions points at the LHC, propagating in the direction tangent to the accelerator arc.

* Let these beams propagating for some distance: some particles will be deviated or stopped, some other will reach the detector.

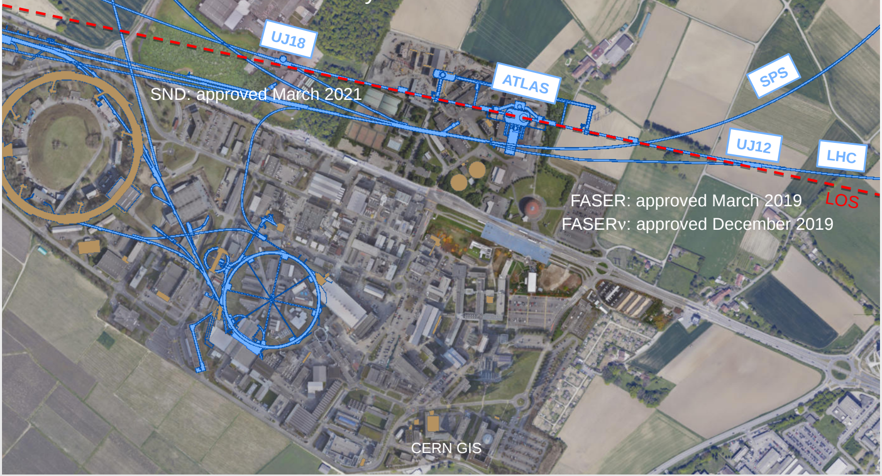
* Pilot experiments, on the tangent to the LHC beam line, at $\sim$ 480 m from ATLAS IP:
  - FASER ($\eta > 9.2$), Faserν ($\eta > 8.5$) and SND@LHC ($7.2 < \eta < 8.4$), all active in taking data during Run 3.



* Detection mechanisms: CC and NC ν and $\bar{\nu}$ induced DIS, DM scatterings on e and A.

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.



Particle Fluxes at far-forward LHC experiments

$*$ Not all kinds of particles produced at the IPs and propagating in the forward region of the LHC can be seen at the location of the experiments: LHC optical elements and rock are on the way.

$*$ Among the particles produced at the IP or nearby, forward ν, μ and some kinds of BSM particles will reach the detectors.

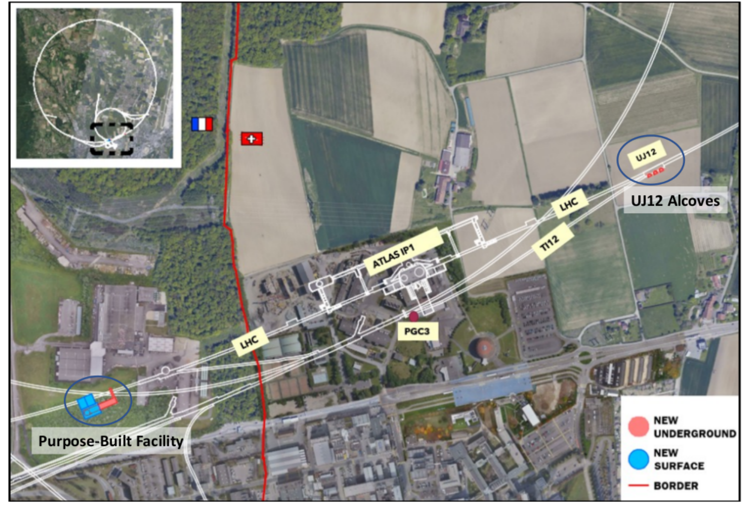
$*$ ν forward fluxes: intense and very energetic, with $\mathcal{O}$(TeV) particles (peak in the energy spectrum much larger than for fluxes seen in other accelerator neutrino experiments, like e.g. DUNE).

$*$ ν search complementary to analyses at ATLAS/CMS/LHCb for which ν are just "missing energy".

$*$ BSM LLPs: searches in the low mass / large $c\tau^0$ domain, complementary to searches at ATLAS/CMS/LHCb for which LLPs decaying beyond the spatial limits of the detector infrastructure are "missing energy".

$*$ Present far-forward experiments limitations: limited size.

Possibilities for a FPF at the LHC



- dedicated facility
- enlargement of one of the existing caverns with alcoves

Experimental options under study within the FPF

- advanced SND@LHC: neutrinos, light DM (two off-axis detectors: FAR with $7.2 < \eta < 8.4$ and NEAR with $4 < \eta < 5$).
- Faserν2: neutrinos, light DM (on-axis, $\eta \gtrsim 8.5$)
- FLArE: neutrinos, light DM and mCP (on-axis, $\eta \gtrsim 7.4$)
- FASER2: decays of LLPs (dark bosons, dark scalars, HNLs, ALPs....) (on-axis, $\eta \gtrsim 7.1$)
- FORMOSA: mCP (on-axis, $\eta \gtrsim 7.4$)

Some additional studies for heavy BSM particles (e.g. SUSY neutralinos) have also been carried out.

As for forward muons, they are currently considered more as a background disturbing the searches, however they also offer a possible prototype for muon beam dump exp. that might be relevant for muon collider.

First observations of far-forward LHC neutrinos

∗ FASER collab., [arXiv:2105.06197]:

A search for neutrino interactions is presented based on a small emulsion detector installed at the LHC in 2018. We observe the first candidate vertices consistent with neutrino interactions at the LHC. A 2.7σ excess of neutrino-like signal above muon-induced backgrounds is measured. These results demonstrate FASERν's ability to detect neutrinos at the LHC and pave the way for future collider neutrino experiments.

∗ FASER collab., [arXiv:2303.14185]:

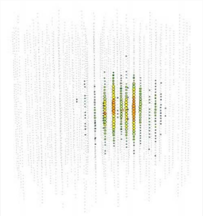
Summary We report the first direct detection of neutrinos produced at a collider experiment using the active electronic components of the FASER detector. We observe 153^{+12}_{-13} neutrino events from CC interactions from ν_μ and $\bar{\nu}_\mu$ taking place in the tungsten-emulsion detector of FASERν. The spatial distribution and properties of the observed signal events are consistent with neutrino interactions, and the chosen analysis strategy does not depend on the quality of the modeling of detector effects in the simulation. For the signal events, the reconstructed charge shows the presence of anti-neutrinos, and the reconstructed momentum implies that neutrino candidates have energies significantly above 200 GeV. This

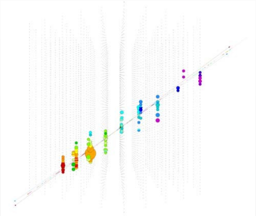
∗ SND@LHC collab., [arXiv:2305.09383]:

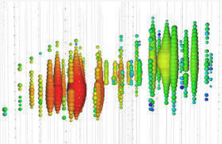
Conclusions - A search for high energy neutrinos originating from pp collisions at $\sqrt{s} = 13.6$ TeV is presented using data taken by the electronic detectors of SND@LHC. We observe 8 candidate events consistent with ν_μ CC interactions. Our muon-induced and neutral-hadron backgrounds for the analysed data set amount to $(7.6 \pm 3.1) \times 10^{-2}$ events, which implies an excess of ν_μ CC signal events over the background-only hypothesis of seven standard deviations.

Other experiments for detecting high-energy neutrinos

* Atmospheric neutrinos at ANTARES, IceCube, KM3NeT, Baikal-GVD...
  track / shower events from CC and NC $\nu + \bar{\nu}$ induced DIS in ice/water.







- lighter targets for DIS than in far-forward LHC experiments
- these experiments distinguish different flavour (like the LHC ones)
- these experiments do not distinguish ν and $\bar{\nu}$ (differently from LHC ones).
- these experiments do not have a ν and $\bar{\nu}$ pseudorapidity cut (differently from LHC ones).

Main sources of far-forward neutrino fluxes at LHC (..............and in the atmosphere)

Nucleon-Nucleon interactions:

$*$ <u>conventional</u> neutrino flux:

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

$*$ <u>prompt</u> neutrino flux:

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

where the decay to neutrino occurs through semileptonic and leptonic decays:

$D^+ \rightarrow e^+ \nu_e X$, $D^+ \rightarrow \mu^+ \nu_\mu X$,

$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm}$, with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \mathrm{X}$

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

QCD opportunities with forward neutrinos during the HL-LHC phase

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New facility: Forward Physics Facility @ CERN capable of hosting a suite of experiments exploiting forward neutrinos produced at one of the LHC interaction points and propagating for several hundred meters in the direction tangent to the accelerator arc

New pilot experiments:
Faser2, Faser-ν, SND@LHC, MilliQan

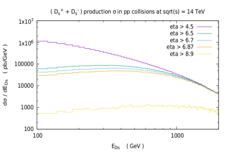
Physics Opportunities:
* Proton Parton Distribution Functions
* Nuclear Parton Distribution Functions
* NP QCD and Tuning of Monte Carlo event generators
* Forward charged pions and kaons
* Forward heavy-flavoured hadrons

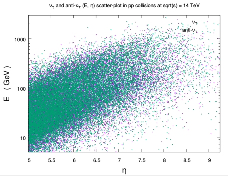
Proton Parton Distribution Functions
* Low x ($x < 10^{-6}$) gluon at $Q^2 > 1$ GeV^2 not probed by other experiments so far!

Nuclear Parton Distribution Functions
* Measurements of CC and NC ν - A and $\bar{\nu}$ - A DIS cross-sections using various targets
* u and d quark flavour separation
* DIsentangling strange sea asymmetries
* Complementary to EIC e-A scattering studies

NP QCD and Tuning of MC event generators
* New data for testing the robustness of phenomenological models describing NP physics in MC (e.g. NP MPI, beam remnant effects, hadronization, branching fractions) and tuning their parameters.

Forward heavy-flavour
* NP effects in heavy-flavour production
* Interplay with perturbative effects
* Universality of FF
* Intrinsic heavy-flavour and higher-twist





Forward charged pions and kaons
* NP effects in light-flavour production
* Cosmic Ray EAS applications

Open questions:
* how to disentangle SM and BSM effects ?
* how to measure forward lepton fluxes and disentangle them from cross-sections ?

See also W. Bai, M. Diwan, M.V. Garzelli, Y.-S. Jeong, M.H. Reno, *"Far-forward neutrinos at the LHC"*, hep-ph/2002.03012, JHEP **2006** (2020) 032.

Work supported by BMBF contract O5H18GUCC1

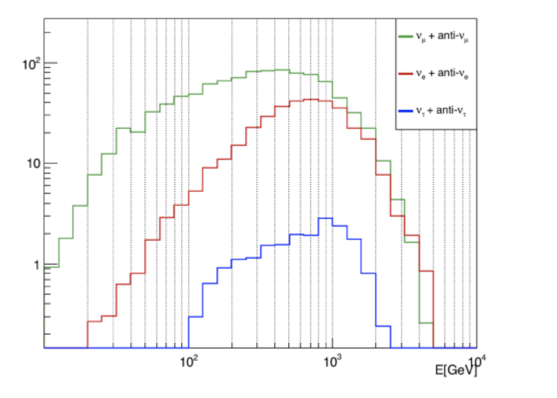
For further info:
* 2nd Forward Physics Facility Meeting online – 27 – 28 May 2021
https://indico.cern.ch/event/1022352 !Registration open!
* Forward Physics Facility Kick-off meeting – 9 – 10 Nov 2020

presented at the APS Meeting "Quarks to Cosmos", April 2021

Neutrino event rates

* The detectors will measure observables from the **convolution** of **fluxes** (production + propagation) and **interaction** σ with target.
* Capability to distinguish might be more important for SM precision constraints than for BSM searches...
* For example, SM objectives of the LHC ν experiments may include:
  - Constraining forward particle production in *pp* collisions (of interest for better modelling soft physics and tuning the related parameters in MC event generators): it works well under the assumption: *"we precisely know neutrino cross-sections"*.
  - Constraining PDFs/nPDFs through neutrino DIS with target in detector (of interest for SM and BSM programs at HL-LHC and for atmospheric prompt neutrinos): it works under the assumption: *"we precisely know neutrino fluxes"*.
* Attention to the consistency between predictions for fluxes and cross-sections, often done with different tools!

MC predictions of energy distributions of CC DIS ($\nu+\bar{\nu}$)-induced events



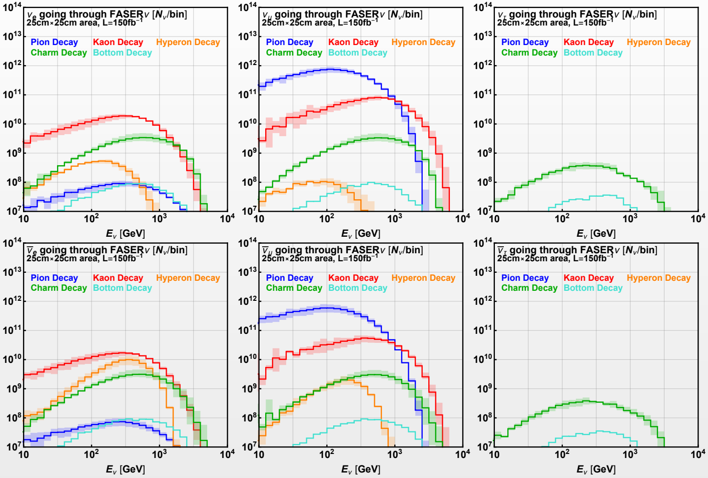
from SND@LHC technical proposal (2021)

∗ Energy spectra of the different kinds of CC DIS interacting neutrinos. The normalization corresponds to $L_{int} = 150$ fb^{-1} and 830 Kg of Tungsten.

∗ Dominance of conventional component (especially at low E).

∗ No conventional contribution to ν_τ in both cases.

Examples of MC predictions of forward ($\nu+\bar{\nu}$) fluxes



from Faserν collab. [arXiv:1908.02310]

Estimated number of ν impinging on the transverse area of the FASERν detector.

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

How to estimate a more reliable uncertainty band ?

Why making Φ predictions is so difficult ?

* Partly, because we are interested in kinematical regions, where non-pQCD effects may become important.

* Non-pQCD aspects of QCD not in so good control as the pQCD ones:
  – pQCD: clear recipes for calculating $\mathcal{A}$ from a Lagrangian.
  – non-pQCD: realm of phenomenological models
  fits of their parameters to data
  tuning efforts

* Non-pQCD effects occur in every pp collision. The experimental cuts adopted in many SM and BSM analyses with the LHC central detectors helps reducing their importance (with respect to the pQCD ones).

see also LHCf talk by O. Adriani at this Workshop

ν_τ and $\bar{\nu}_\tau$ fluxes in hadronic collisions

* It is the easiest to predict, being dominated by the process

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

  where the decay to neutrinos occurs mainly through

  $D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm}$ with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + X$.

* pQCD applicable down to $p_T = 0$ ($m_Q \neq 0$),
  but non-pQCD aspects also matter!

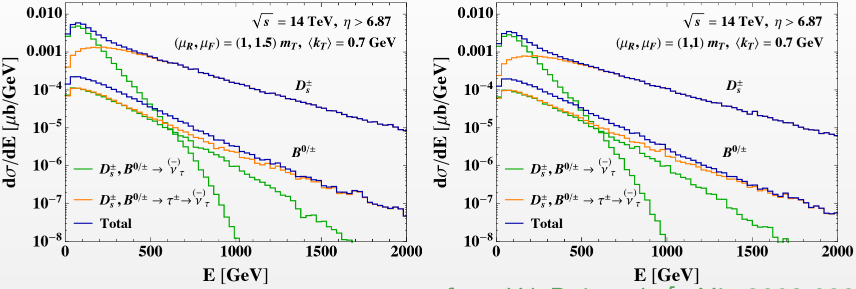
* Heavy flavours decay promptly.

* The point of production of tau neutrinos and taus from $D_s^{\pm}$ has distance
  $d = \gamma c \tau_{D_s} \sim E_{D_s}/m_{D_s} \cdot 150\ \mu\mathrm{m} \sim 1.5$ - 15 cm for $E_{D_s} = 200$ GeV - 2 TeV.

* Similarly for tau neutrinos from $B^{\pm}$,
  $d = \gamma c \tau_{B\pm} \sim E_{B\pm}/m_{B\pm} \cdot 496\ \mu\mathrm{m} \sim 1.9$ - 19 cm for $E_{D_s} = 200$ GeV - 2 TeV.

* And for neutrinos from τ decay,
  $d' = \gamma c \tau_\tau = E_\tau/m_\tau \cdot 87.11\ \mu\mathrm{m} \sim 0.98$ - 9.8 cm.

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 ?

Heavy-quark production in hadronic collisions

* Heavy quarks are mostly produced in pairs in the Standard Model.
* This process is dominated by QCD effects.

* Collinear factorization theorem is assumed:

$$d\sigma(N_1 N_2 \to Q\bar{Q} + X) = \sum_{ab} PDF_a^{N_1}(x_a, \mu_F^2) \otimes PDF_b^{N_2}(x_b, \mu_F^2) \otimes$$
$$\otimes \; d\hat{\sigma}_{ab}(x_a, x_b, \mu_F^2, \mu_R^2, \alpha_s(\mu_R^2), m_Q)$$

d$\hat{\sigma}$: differential perturbative partonic hard-scattering cross-section,

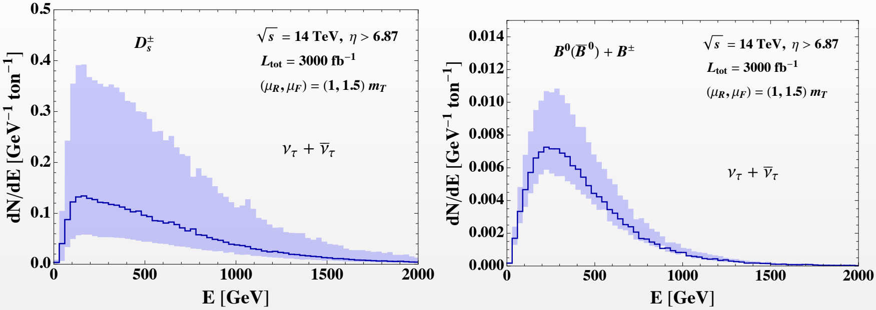
μ_F, μ_R reabsorb IR and UV divergences,

PDFs: perturbative evolution with factorization scale μ_F,
non-perturbative dependence on $x = p^+/P_N^+$.

QCD uncertainties

* μ_F and μ_R choice: no univocal recipe.
* Approximate knowledge of heavy-quark mass values m_Q (SM input parameters).
* Choice of the Flavour Number Scheme (several possibilities).
* PDF (+ $\alpha_S(M_Z)$) fits to experimental data.

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



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

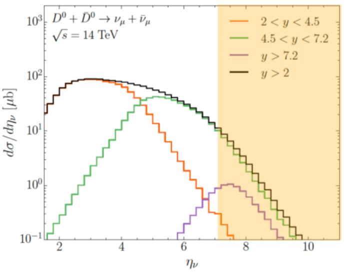
∗ Huge uncertainty band from state-of-the-art QCD calculations.

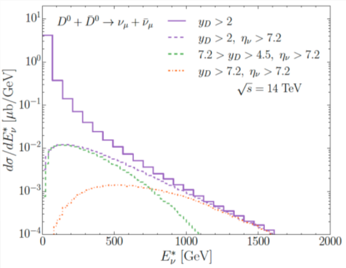
∗ Missing higher-order pQCD contributions are probably large.

∗ In case of bottom production, uncertainty is smaller (+60%, -20%) than for charm (+300%, -60%) in relation to the fact that $m_b > m_c$ $\Rightarrow \alpha_S(\mu_R = m_b) < \alpha_S(\mu_R = m_c)$.

∗ Additional uncertainties due to focus in forward region.

Prompt ν fluxes at the LHC



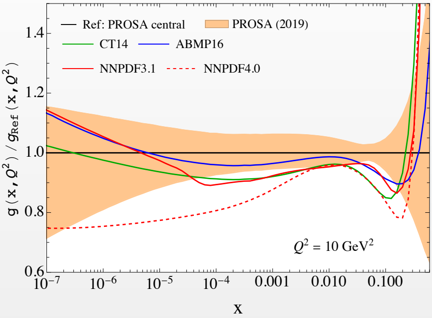


$*$ At the LHC, charmed mesons with $4 < y_c < 7$ give rise to neutrino populating a wide rapidity spectrum, with a maximum around $\eta_\nu \sim 5$.

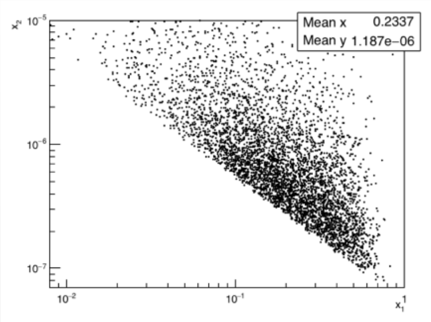
$*$ These neutrinos constitutes the majority of neutrinos for $\eta_\nu \gtrsim 7.2$ (region probed by SND@LHC, and at future FPF).

$*$ The energy spectrum of these neutrinos is peaked at $\sim$ 100 GeV in CM frame, but extends also to the TeV. For $E_\nu \sim 700$ GeV half neutrinos at the LHC come from charm with $4.5 < y_c < 7.2$, whereas another half come from charm with $y_c > 7.2$. On the other hand, most energetic neutrinos at the LHC come from charmed mesons with higher rapidities.

PDFs uncertainties at low and large-x and x coverage of forward ν LHC exp.



W. Bai et al., [arXiv:2212.07865]



SND@LHC technical proposal (2021)

$*$ Differences in gluon PDFs at large x are not covered by the uncertainties associated to each single PDF set.

$*$ The coverage of forward ν experiments can help constraining PDFs at extreme x-values (actually more extreme than what is needed for atmospheric prompt ν at the PeV scale).

ν fluxes in the atmosphere vs. LHC

$*$ production mechanisms: the same as at the LHC, complicated by the presence of nuclear effects in pO collisions in the atmosphere.

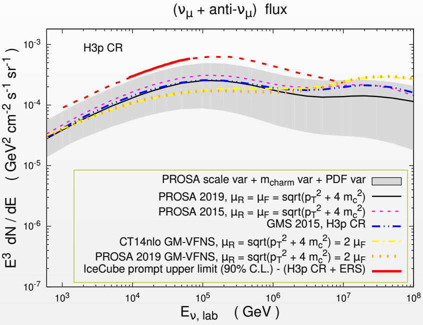
$*$ E_ν energy range: higher, because the most energetic CR interact with the atmosphere at $\sqrt{s_{NN,CR}} \sim 300$ TeV, whereas $\sqrt{s_{NN,LHC}} = 13$ - 14 TeV,

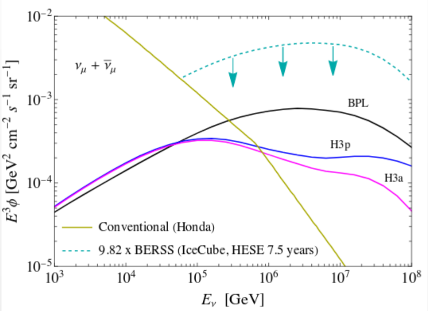
$*$ Rapidity coverage probed: wider in the atmosphere, than in far-forward ν experiments at the LHC ($\eta_\nu \gtrsim 7$)

$\Rightarrow$ Importance of very forward physics aspects is enhanced in collider studies with forward experiments, w.r.t. neutrino telescopes.

$*$ Complication at LHC: geometry of the line beam affects ν_e and ν_μ fluxes. ν_τ unaffected, like in the atmosphere.

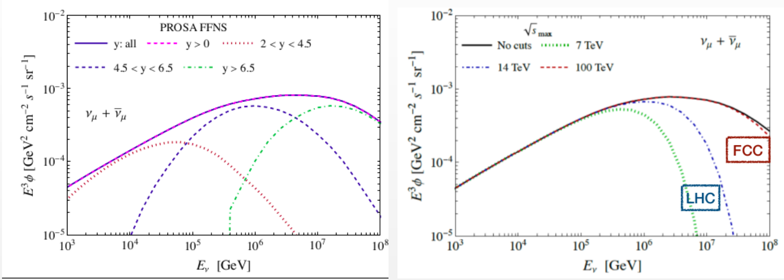
Prompt atmospheric ν fluxes: uncertainties and IceCube upper limits





* Theory uncertainties on prompt ν are large (due not only to QCD, but also to CR composition)
* IceCube has put some constraints on prompt neutrinos.

Prompt atmospheric ν fluxes and LHC phase-space coverage

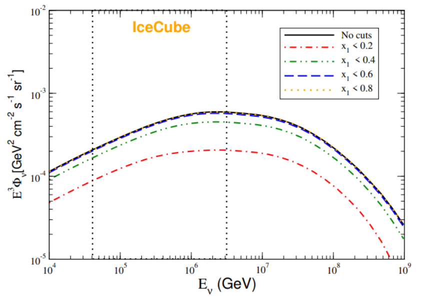


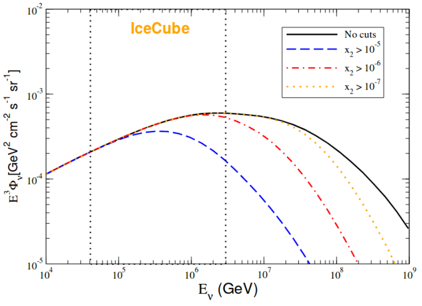
* To connect to prompt ν fluxes at the PeV, LHC measurements of charm production should focus on the region $4 < y_c < 7$.

* The $\sqrt{s} = 14$ TeV at LHC is in any case a limitation, FCC would be better (see also analysis in V. Goncalves et al, [arXiv:1708.03775]).

* Exploring the connection between (E_ν, y_ν) and y_c reveals that there is some kinematic overlap between the heavy-flavour production region explored in far-forward ν experiments at the LHC and in the atmosphere.

Prompt atmospheric ν fluxes and large-x PDFs





, *from V. Goncalves et al. [arXiv:1708.03775]*

∗ A robust estimate of large x effects is important for determining the normalization of prompt atmospheric neutrino fluxes

∗ Region particularly relevant: $0.2 < x < 0.8$, partly testable through ν experiments at the LHC.

∗ On the other hand, for ν at the PeV scale, knowledge of PDF down to $x > 10^{-6}$ is enough.

Strange sea in (n)PDFs

$*$ At present, one of the most uncertain partons in both proton and nuclear PDF fits. In some cases, results are consequences of strict assumptions: e.g. $u(x) = d(x) = s(x) = \bar{s}(x)$ or fixed values of $f_s = \bar{s}/(\bar{s} + \bar{d})$ or $R_s = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$

$*$ Big uncertainties and attitude partly motivated by the fact that data from different experiments seem to be partially incompatible among each other.

$*$ Legacy data used in PDF fits to determine strange sea:

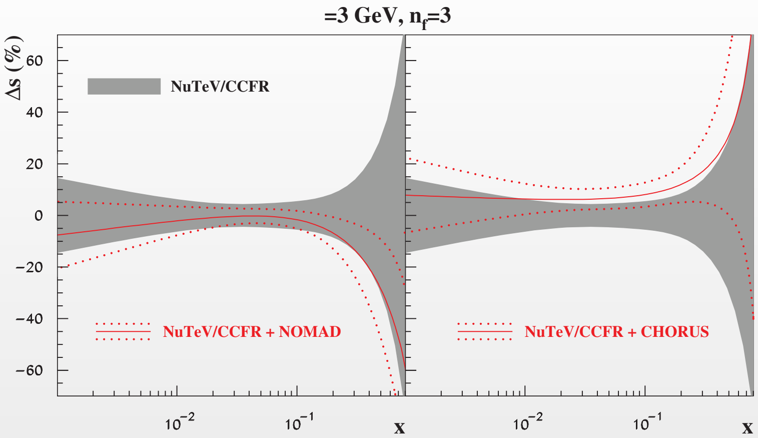
- massive high-density detectors providing dimuon data (CDHS, CDHSW, CCFR, CharmII, NuTeV, NOMAD)
- bubble chamber data (BEBC)
- nuclear emulsions (E531, CHORUS)

$*$ The incapability of simultaneously obtaining a good fit of all previous ones has led the PDFs and nPDF collaborations to discharge some data (e.g. NuTeV).

$*$ Additionally, recent precise LHC data (in particular Drell-Yan) turn out to also be sensitive to strange quark distributions. They point to a larger strange component with respect to the dimuon data, generating some tension with the latter.

$*$ Important to quantify strange sea in nPDF even to understand if the observed enhanced abundance of produced strange anti-barions in AA collisions can be ascribed to the onset of a QGP.

Strange sea from fixed-target data



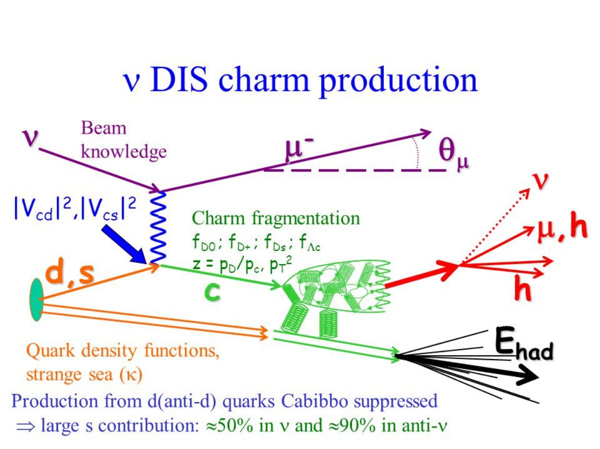
from S. Alekhin, ABM PDF fits

* NOMAD data (dimuon/inclusive CC DIS) pull down s for $x > 0.1$.
* CHORUS data pull up s.
* DY data (not shown) pull up s for $x \lesssim 0.1$.

Charm production in ν-induced CC DIS and strange sea

∗ Charm/Anticharm production in CC DIS has direct sensitivity to $s(x)$, $\bar{s}(x)$ at LO

∗ One can separate $s(x)$ and $\bar{s}(x)$ by disentangling ν and $\bar{\nu}$ events.



picture by G. De Lellis

Conclusions - high-energy forward ν

$*$ Some of the opportunities of far-forward LHC neutrino experiments during Run 3 and, with much higher-statistics, Run 4:

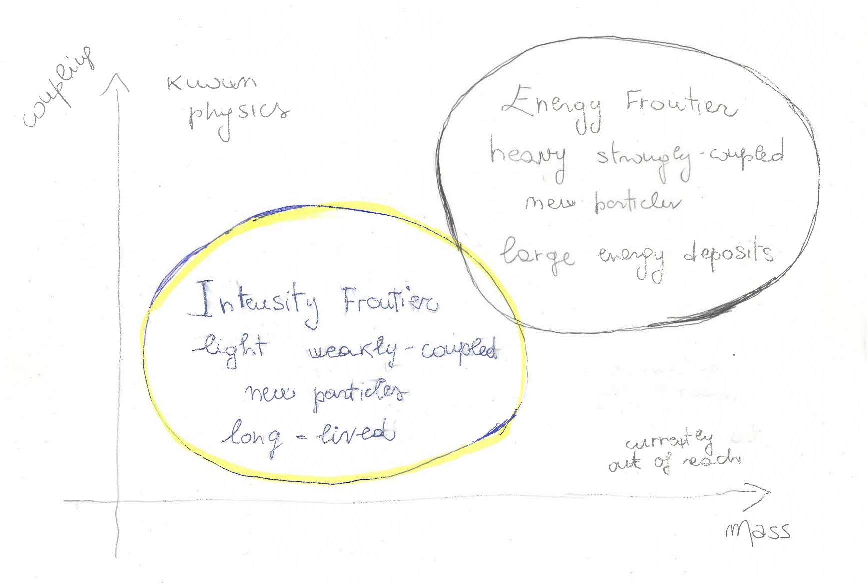
- gluon pPDFs at large and low x,
- strange sea nPDFs,
- help disentangling pQCD and non pQCD effects in heavy-flavour production,
- help constraining non-pQCD models in MC event generators for particle and astroparticle physics.

$\Rightarrow$ Synergy LHC-EIC-astroparticle physics.

$*$ There is some kinematical overlap between the charm hadron production region explorable in far-forward experiments at the LHC and the one explorable in VLVνT's.

$*$ Atmospheric ν's with $E_{\nu,LAB} \sim \mathcal{O}(\text{PeV})$ mostly come from charm produced within LHC $\sqrt{s}$ in the rapidity range $4.5 < y_c < 7.2$, which in turn produce neutrinos even in the ν rapidity range of the SND@LHC detector $\eta_\nu > 7.2$ and future (like in the FPF).

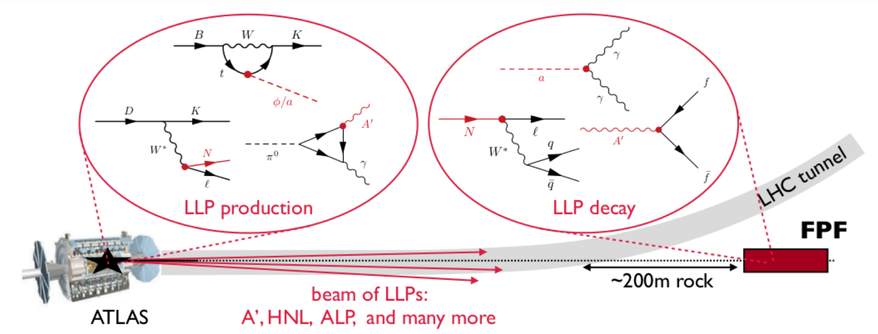
Which BSM particles can be better studied in the LHC forward region ?



Search for light BSM particles

Most (but not all) BSM searches at the FPF focus on:

- LLPs (vectors, scalars, fermions, pseudoscalars) exclusively coupled to the SM in minimal models, decaying in the FPF detectors:



- LLPs in non-minimal models

- LLPs coupled to light DM, with DM decaying or interacting in the FPF detectors.

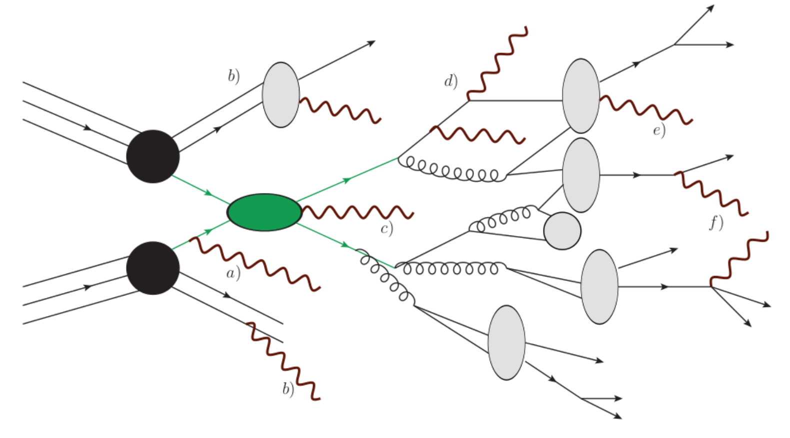
How are LLP produced ?

Depending on the LLP, the production mechanism can be:

- Meson decays at the IP
- proton bremsstrahlung
- Drell-Yan
- ISR, FSR
- hadronization
- emissions from beam remnants

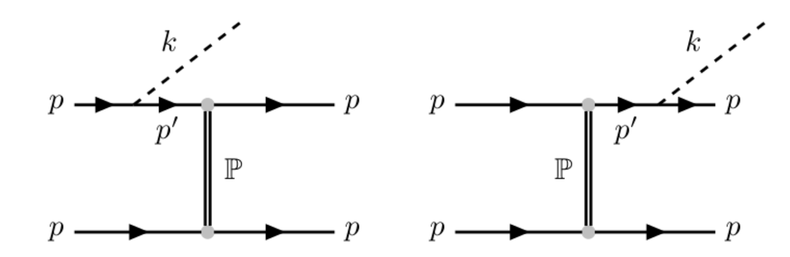
To have reliable production for the LLP flux, we need to control all these processes, starting from reliable predictions in the forward region for the SM case, and extending them to BSM !

Example: dark photon production



Dark photons are under incorporation in Shower Monte Carlo event generators

Example: dark scalar radiation from proton bremsstrahlung



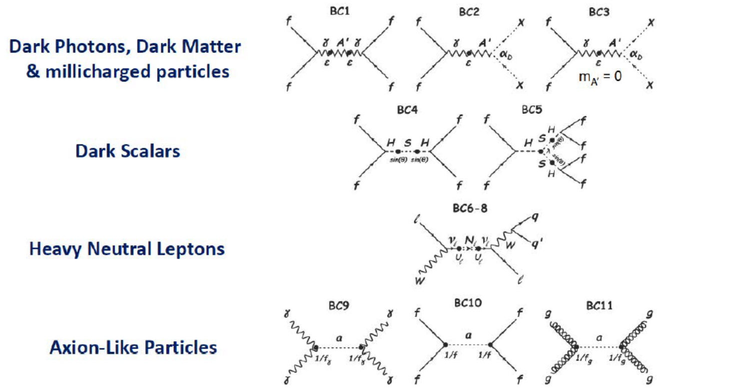
- ISR and FSR in *pp* quasi-elastic scattering (*t*-channel pomeron exchange)

- ISR-FSR interference suppress dark scalar emission.

- On the other hand in non-single diffractive scattering, interference is not expected.
- Analogous considerations work for dark photons.

PBC BSM Benchmark Cases

The BSM WG selected a set of theoretically and phenomenologically motivated target areas used as benchmarks models to explore the physics reach of the received proposals and put them into the worldwide landscape.



from M. Lamont, PBC presentation @ MITP, november 2020

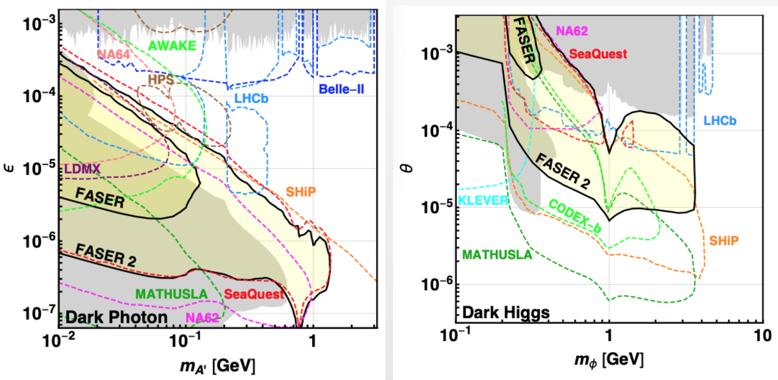
∗ 11 models for light, weakly-interacting particles (LLPs, FIPs)

∗ BC1, BC4-11 covered by FASER, FASER2; BC2 and BC3: other FPF exper..

BCs 1, 4-11: LLPs at FASER and FASER2

∗ Run-3 integrated luminosity is enough for FASER to discover new physics for some of the Benchmark Cases.

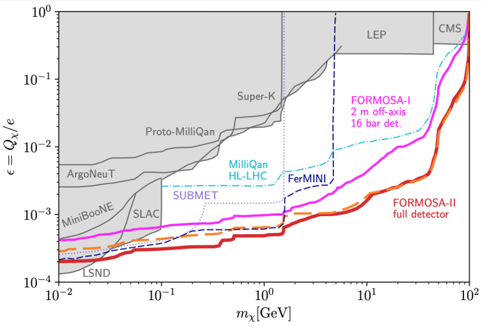
∗ FPF will provide space to upgrade FASER (R = 10 cm, L = 1.5 m) to FASER2 (R = 1.0 m, L = 5 m), either greatly enhancing sensitivity (e.g. for A' - visible mode) or by providing new prospects (e.g. for S), complementary to other experiments.



from FASER Collaboration, [arXiv:1811.12522]

BC3: Milli-charged particles

* This is currently the target of the MilliQan experiment, near the CMS IP.
* MilliQan Demonstrator already probes an otherwise uncovered region. Full MilliQan planned to run in the same location at HL-LHC. However, sensitivity can be improved significantly at the FPF (FORMOSA)



from MilliQan/FORMOSA

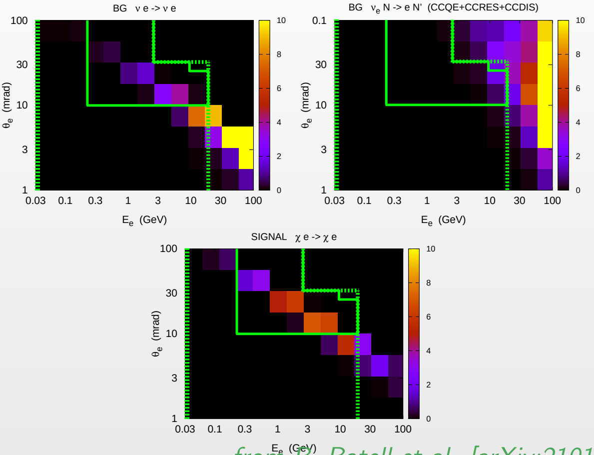
Light DM searches at the FPF: a simple testable model

* Hypothesis: DM particles χ in a hidden sector coupled to the SM through a dark photon A' with $m_\chi < m_{A'} << m_{EW}$.
  Parameter space $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$
* A' produced either by $pp \to ppA'$ (proton bremsstrahlung) or through $pp \to \pi^0, \eta, ... + X \to A'\gamma + X$
* followed by $A' \to \chi\,\chi$ decay.
* Signal at FPF detectors (LAr TPC or emulsion detector):
  $\chi e^- \to \chi e^-$
* Backgrounds at FPF detectors:
  - CC $\nu_e e^- \to \nu_e e^-$, $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$
  - NC $\nu_i e^- \to \nu_i e^-$, $\bar{\nu}_i e^- \to \bar{\nu}_i e^-$
  - CC and NC νN interactions.
  - $\mu \to \mu\gamma \to \mu e^+ e^-$

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

Light DM searches: signal/background discrimination

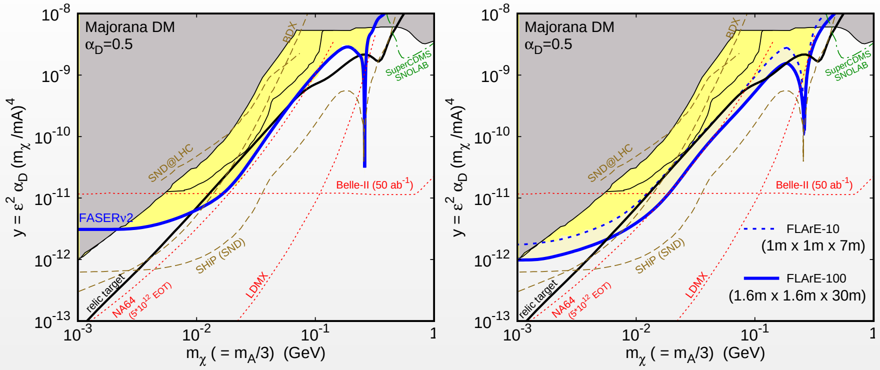
* ν induced background can be eliminated because signal and background occupy different regions of the $(E_{e,rec}, \theta_{e,rec})$ plane.



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

* μ induced background can strongly be reduced by sweeper magnets or active μ vetos.

Exclusion bounds for light Majorana DM search



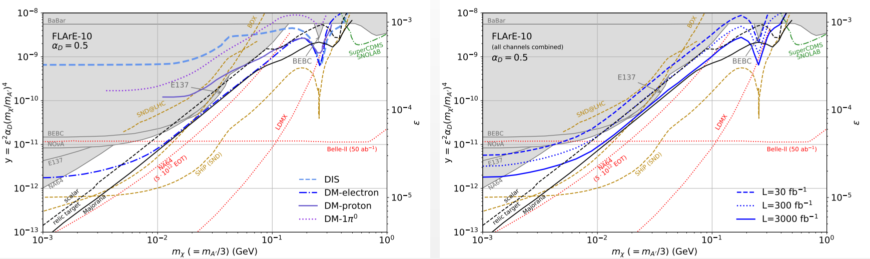
from B. Batell et al. [arXiv:2101.10338]

∗ LArTPC 10-ton detector increases exclusion bounds w.r.t. emulsion (Faserν2).

∗ Sensitivity to the region where χ has the correct thermal relic density.

∗ Complementary info w.r.t. missing energy experiments, that do not see χ scattering.

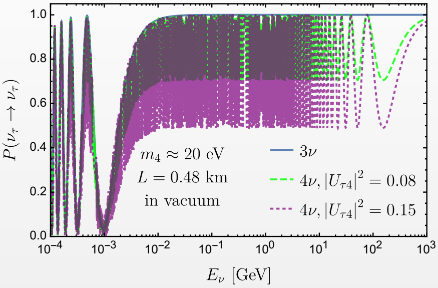
Exclusion bounds for light Majorana DM search

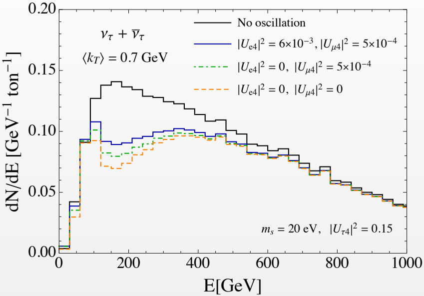


from B. Batell et al. [arXiv:2107.00666]

∗ Extension of the previously considered exclusion bounds in the large m_χ region, thanks to the additional identification and analysis of $\chi + A$ collisions.

Other physics opportunities/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 - BSM

$*$ Far-forward experiments offer the opportunity for a reach BSM (and SM) program, exploiting the production of LLPs at one of the LHC IPs, their decay in SM or DM, and DM + e and DM + A scatterings in the detectors.

$*$ FASER/FASERν/SND@LHC able to provide competitive limits in exclusion plots during Run 3.

$*$ A Forward Physics Facility, ready for the HL-LHC phase, can offer a unique opportunity to expand the program of LLP/FIP/DM searches in the "forward" direction.

$*$ Crucial questions, considering the BSM production and decay mechanisms:
- how well do we control forward SM particle production and decay ?
- how well do we control SM ν + e and ν + A backgrounds ?

Thank you for your attention!