Searches for Long-lived Particles & Neutrinos with New detectors at the LHC

FASER$^\nu$, SND@LHC, MoEDAL-MAPP

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LHC experiments typically focus on heavy, strongly interacting particles

- Require large transverse momenta of detected particles
- Produced ~isotropically and at relatively low rates
The landscape of new particles at colliders

“LIFETIME” A characteristic of weakly interacting particles

Distinct signatures

Opportunity for exploration!

- Motivated by the lack of results in “traditional” searches and new physics scenarios

Explosion of ideas!
Build a new detector to profit the LHC collisions to find elusive LLPs and TeV neutrino (and muon) beams. Perfect detector would
- Have 0 background
- Have 100% coverage
- Be very cheap (no civil works needed.)
+ Long-lived (neutral) particles (LLP) that decay in detector volume to charged particles
+ Collider-originated neutrino measurements
  high-energy neutrinos in unexplored energy region (~TeV)
FORWARD SEARCH EXPERIMENT

From searches for weakly interacting particles to first measurements of collider neutrinos

In search for long-lived physics

To detect and measure collider neutrinos.
Overview

Searches for new weakly-interacting light long-lived particles

- New particles produced in decays of light mesons,
- copiously present at zero angle,
- escaping detection in ATLAS/CMS

➢ 2x10^{-6} % solid angle but still O(10^{15}) \pi^0 in RUN 3!

- situated along the beam collision axis line of sight (LOS) in T112 tunnel (former injection tunnel for LEP)
- 480 m from IP1 (ATLAS) with Transverse radius of 10 cm covering the mrad regime (\eta>9.1)
- After beams start to bend
- A few meters from the LHC beam line

● Distinctive detector signature: \sim TeV long-lived particles produced in the forward region

An almost perfect location
- Shielded by LHC components and rock
- Low radiation levels
- no radiation-hard electronics needed
**Key signatures**

- **Dark photon ($A'$)**
  - **Ballpark numbers for $A'$:**
    - Momentum of 1 TeV
    - Mass of 100 MeV
  - **Decay products collimated requirements for magnetic field & high resolution tracker**

**Physics potential:** *Phys. Rev. D 99, 095011*
MoEDAL-The Monopole and Exotics Detector at the LHC

BSM scenarios through searches for:
- highly ionizing particles, such as magnetic monopoles
- multiply electrically charged particles, as avatars of new physics.

MoEDAL physics program
The LHC’s First Dedicated Search Experiment

✦ MAPP the MoEDAL Experiment will be sensitive to 3 clear avatars of new physics:
  ✦ Highly ionizing particles (HIPS)
  ✦ Mini-charged Particles (mQPs)
  ✦ Long-lived Particles (LLPs)

**Overview**

Consists of 2 sub detectors

- **MAPP-LLP**: The very long-lived weakly interacting particle detector
- **MAPP-mQP**: The core milli-charged particle detector
  - Particles with charges $\ll 1e$

- **MAPP-1 (mQP+LLP)** for RUN 3

Deployed in the UGC8 Gallery adjacent to MoEDAL’s intersection point IP8
- ~55m away from the IP
- @ an angle of $5^\circ$ w.r.t beam axis
- Protected by
  - 100m of rock overburden
  - 25 m of rock from IP

“Box-within-a-box” structure to detect charged tracks from neutral-particle decays

- Constructed of 3 nested boxes formed from scintillator strip hodoscope planes
- The readout structure are scintillator strips in an x-y configuration readout by SIMPs
Benchmark Process:

- Reach for MAPP-1 (30 fb⁻¹ /300 fb⁻¹) for the scenario where the Higgs mixing portal admits inclusive
  - $B \rightarrow X_s \phi$ decays
  where $\phi$ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\theta \ll 1$

Promising physics reach for MAPP-LLP also for R-parity violating SUSY and sterile neutrino models [e.g. Dreiner et al, 2008.07539 & 2010.07305, respectively]
Neutrinos at the LHC

- ATLAS provides an intense and strongly collimated beam of TeV-energy neutrinos along beam collision axis.
  - huge flux of neutrinos in the forward direction, mainly from: \( \pi, K \) and D meson decay
- The neutrino beam passes through the side tunnels TI12 and TI18, ~480 m downstream from ATLAS,
  - shielded by ~100 m of rock from the IP,
  - providing a natural location for LHC neutrino experiments

ATLAS provides an intense and strongly collimated beam of TeV-energy neutrinos along beam collision axis.

- huge flux of neutrinos in the forward direction, mainly from: \( \pi, K \) and D meson decay
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  - providing a natural location for LHC neutrino experiments

Symmetric to TI12 tunnel where FASER is located

Angular acceptance: \( 7.2 < \eta < 8.6 \)

Identification and measurement of the three neutrino flavours, \( \nu_e, \nu_\mu, \nu_\tau \) detection of feebly interacting particles

FASERv: will be placed in front of the FASER main detector

1.2-ton emulsion based detector

- distinguish all flavor of neutrino interactions.
FASERν in FASER

Measurement at highest man-made neutrino energies

• A high-intensity beam of neutrinos will be produced in the far-forward direction.
• FASERν will be centered on the LOS (in the FASER trench) to maximize fluxes of all neutrino flavors.
• Expect to collect ~10000 CC interactions (distinguishing the flavors) in LHC-Run3 (2022-2024). {F. Kling, Forward Neutrino Fluxes at the LHC, arXiv:2105.08270}

Will be installed in October for Run3!

Aims:
• Detect collider neutrinos for the first time.
• Probe neutrino interactions in an energy range where neutrino cross sections are unconstrained, especially tau neutrinos.
• Probe BSM neutrino physics…
• Expected cross section reach: extends current measurements already with 150/fb^{-1}

Pilot Run in 2018 (LHC Run-2)

Aim: demonstrate neutrino detection at the LHC for the first time

- Performed measurements in the tunnels TI18 and TI12, 480 m from the ATLAS IP.
- For neutrino detection, a 30 kg emulsion detector was installed in TI18 and 12.2 fb⁻¹ data was collected.

- Analyzed target mass 11 kg
- 18 neutral vertices were selected
- by applying # of charged particle ≥ 5, etc.
- Expected signal 3.3⁺1.7₋0.9 events, BG 11.0 events

This result demonstrates detection of neutrinos at the LHC!

In BDT, an excess of neutrino signal is observed. Statistical significance 2.7σ from null hypothesis

preparing for data taking in LHC Run-3!
SND@LHC A newly proposed, compact and stand-alone experiment designed to:
- measuring neutrinos produced at the LHC in an unexplored pseudo-rapidity region
- searching for feebly interacting particles (FIP) through scattering off atoms in the detector target

Detector optimised for neutrino searches in a region where they act as a probe of heavy (mostly charm) quark production
- BSM searches possible (relying on the topology and on the time-of-flight measurements), sensitivity under evaluation

LEPTON FLAVOUR UNIVERSALITY TEST

- The identification of three neutrino flavours in the SND@LHC detector offers a unique possibility to test the Lepton Flavor Universality (LFU)
- Data taking will start in early 2022

The measurement of the $\nu_e/\nu_\mu$ ratio can be used as a test of the LFU for $E>600$ GeV
- Sensitive to $\nu$-nucleon interaction x-section ratio of two neutrino species
Refurbishment of TI12 to be an experimental site was completed in Winter 2020.

All detectors have been installed in TI12 as of March 2021

Already starting to collect cosmic-ray data.

Aiming to start data taking in LHC Run-3 from 2022 for:

- discovery of a light weakly- coupled particle in MeV-GeV range

Potential to increase sensitivity with FASER 2 upgrade for HL-LHC:

- opportunity to probe more benchmarks

FASER2 (HL-LHC)

MoEDAL-MAPP (Run3)

will be sensitive to 3 clear avatars of new physics: HIPs, mQPs and LLPs

- Successful mQP prototype tested during LHC Run 2.
- Full detector planned for LHC Run 3.

MoEDAL-MAPP-1 is planned for 2022/UGC1 gallery must be upgraded to house MAPP in 2021/22.

Envisage approval in 2022 and the start of data taking in 2023.

MoEDAL-MAPP-2 (HL-HLC) installed for Run-4 will give a greater fiducial volume for the LLP search
FASER\textsubscript{ν} (Run 3) ▶ Will register neutrinos from a collider for the first time

▪ Design and strategy are all defined
  ▶ Will be installed in October 2021.
▪ Neutrino analysis from Pilot run available
▪ First neutrino interaction candidates at the LHC submitted to journal: \texttt{arXiv:2105.06197}

▪ Aiming data-taking at LHC Run3 in (2022-2024). 
  \~10000 n CC interactions (distinguishing the flavours) are expected

FASER\textsubscript{ν2} (HL-LHC) ▶ Planning neutrino measurements in the HL-LHC era.

▪ A large detector for precision $\nu\tau$ physics with 10-30 tons of target

SND@LHC recently approved (March 2021) ▶ aiming to register \~2000 n CC interactions (distinguishing the flavours) in 2022-2024

▪ Detector under construction
▪ Data taking will start in early 2022
▪ Possible extensions beyond Run3 would highly benefit from the development of a Forward Physics Facility
Thank you for your attention!

Special Thanks to: Vasiliki Mitsou, Jamie Boyd, Jonathan Lee Feng, Zhen Hu, Xabier Cid Vidal, Emma Torro Pastor, Niki Saoulidou, Josef Francisco Zurita
FASER collaboration:

- Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC
- First neutrino interaction candidates at the LHC
- FASER's Physics Reach for Long-Lived arXiv:1811.12522
- Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC arXiv:1908.02310

+ several theory papers:
More information: https://faser.web.cern.ch/physics/publications

MoEDAL-MAPP:

- Webpage: https://moedal.web.cern.ch/moedal-detector
- LLP2021 workshop: James Pinfold
- Snowmass21-EF9_EF8
- MoEDAL – a new light on the high-energy frontier
- MoEDAL physics results and future plans: Vasiliki A. Mitsou
- MoEDAL, FASER and future experiments targeting dark sector and long-lived particles

SND@LHC:

- Technical proposal: LHCC-P-016, 22 Jan 2021
- Experiment approval: Grey Book database, 17 Mar 2021
- Experiment website: http://snd-lhc.web.cern.ch/
Timeline

April 2020!

November 2020!

March 2021

April 2021

May 2021!

All equipment for the new particle searches are installed

Emulsion detector
Detector Design

Searches for new weakly-interacting light long-lived particles

**FASER:** tracker and calorimeter, detects LLP decay to pair of TeV charged tracks

- 1.5-meter magnetized decay volume
- 2-meter magnetic spectrometer
  - Three tracking stations
- Electromagnetic calorimeter
- Three scintillator stations for triggering, veto and precise timing
- Aperture (10 cm radius) and length strongly constrained by available space

Kristof Schmieden

Recycling existing spare modules:
- ATLAS SCT modules (Tracker)
- LHCb ECAL modules (Calorimeter)

**arXiv:1812.09139**
BEYOND FASER ?-backup

Searches for new weakly-interacting light long-lived particles

Physics potential: Phys. Rev. D 99, 095011
FASER 2 is a speculative extension for the HL-LHC

Potential to increase sensitivity with FASER 2 upgrade for HL-LHC

<table>
<thead>
<tr>
<th>Benchmark Model</th>
<th>Label</th>
<th>Section</th>
<th>PBC</th>
<th>Refs</th>
<th>FASER</th>
<th>FASER 2</th>
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<tr>
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<td>IV A</td>
<td>BC1</td>
<td>[7]</td>
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<td>√</td>
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<td>IV B</td>
<td>—</td>
<td>[30]</td>
<td>√</td>
<td>√</td>
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<tr>
<td>L_i - L_j Gauge Bosons</td>
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<td>IV C</td>
<td>—</td>
<td>[30]</td>
<td>—</td>
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<tr>
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<td>V A</td>
<td>BC4</td>
<td>[26, 27]</td>
<td>—</td>
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<tr>
<td>Dark Higgs Bosons with hSS</td>
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<td>V B</td>
<td>BC5</td>
<td>[26]</td>
<td>—</td>
<td>√</td>
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<td>VI</td>
<td>BC6</td>
<td>[28, 29]</td>
<td>—</td>
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<td>VI</td>
<td>BC7</td>
<td>[28, 29]</td>
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<tr>
<td>HNLs with τ</td>
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<td>VI</td>
<td>BC8</td>
<td>[28, 29]</td>
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<td>√</td>
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<td>VII A</td>
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<td>[32]</td>
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<td>√</td>
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<td>VII B</td>
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<td>VII C</td>
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<td>—</td>
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<td>√</td>
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<tr>
<td>Dark Pseudoscalars</td>
<td>P1</td>
<td>VIII</td>
<td>—</td>
<td>[36]</td>
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</table>

Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity
Beam backgrounds

- FLUKA simulations and *in situ* measurements used to assess expected backgrounds.
- IP1 collisions (shielded by 100m rock)
- Off-orbit protons hitting beam pipe aperture near TI12
- Beam-gas interactions
- Low particle flux along beam axis due to LHC optics.

Fluence rate spectra at FASER (above 10 GeV) for the LHC

Fluence rate (GeV⁻¹ cm⁻² s⁻¹) for muons: 10 GeV threshold

Muons (@L=2×10⁻³⁴ cm² s⁻¹)

<table>
<thead>
<tr>
<th>Energy threshold [GeV]</th>
<th>Charged Particle Flux [cm² s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.40</td>
</tr>
<tr>
<td>100</td>
<td>0.20</td>
</tr>
<tr>
<td>1000</td>
<td>0.06</td>
</tr>
</tbody>
</table>

M. Queitsch-Maitland: FASER
MAPP-2 is an extension of MAPP1 down the UGC1 gallery.

The MAPP-1 technology would be used to provide a cost-effective approach.

MAPP-2 extends MAPP1’s sensitivity.

Run 3, 30 fb$^{-1}$

HL-LHC, 300 fb$^{-1}$
Using the same Higgs mixing portal benchmark

So that is competitive with the SHIP’s

Pair production of right-handed neutrinos from the decay of an additional neutral Z0 boson in the gauged B-L model- Phys. Rev.D100(2019),035005

Luminosity assumed in figure:

- **MAPP-2** \(\rightarrow 300 \text{ fb}^{-1}\)
- **CODEX-b** \(\rightarrow 300 \text{ fb}^{-1}\)
- **FASER-2** \(\rightarrow 3 \text{ Ab}^{-1}\)
- **MATHUSLA** \(\rightarrow 3 \text{ Ab}^{-1}\)
Push the search for the decays of new charged, massive and very long-lived long-lived particles

- After exposure and SQUID scan, MoEDAL MMTs will be monitored for decaying electrically charged particles possibly trapped in their volume.
- Sensitive to charged particles (e, µ, had.) and to photons with energy as small as 1~GeV • Estimated MALL probed lifetimes ~10 yrs.
- MALL planned to be installed during Run-3 at the UGC1 gallery of IP8
Emulsion/tungsten detector, interface silicon tracker, and veto station will be placed in front of the FASER main detector. Allow to distinguish all flavor of neutrino interactions.

- **Muon identification** by their track length in the detector ($8/L_{int}$)
- **Muon charge identification** with hybrid configuration → distinguishing $\nu_\mu$ and $\bar{\nu}_\mu$
- **Neutrino energy** measurement with ANN by combining topological and kinematical variables

- FASER spectrometer with 0.55T magnets

- Interface silicon tracker

- **Emulsion/tungsten detector**
  - 770 1-mm-thick tungsten plates, interleaved with emulsion films
  - 25×30 cm$^2$, 1.1 m long, 1.1 tons detector ($220X_0$)
**FASERν**: tungsten emulsion detector in front of FASER

- 3D tracking detector, 50 nm precision, no timing
- Total mass 1.2 tons, 285 X₀, 10.1 λ_int
- Needs to be exchanged every ~3 months (during technical stops) to control track density \( \lesssim 1 \times 10^6 \) tracks/cm³
- To be installed before data taking in 2022
- 10 emulsion detectors in total needed 2021-20 data.

<table>
<thead>
<tr>
<th>Interactions</th>
<th>Mean energy</th>
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<tbody>
<tr>
<td>νₑ + νₑ</td>
<td>~1300</td>
</tr>
<tr>
<td>νµ + ν¯¯µ</td>
<td>~20400</td>
</tr>
<tr>
<td>ντ + ν¯¯τ</td>
<td>21</td>
</tr>
</tbody>
</table>

Assumptions: tungsten emulsion detector (25 cm x 25 cm x 100 cm), 14 TeV, 150 fb⁻¹, Eν > 100 GeV
Expected neutrino event rate in LHC Run-3

- A high-intensity beam of neutrinos will be produced in the far-forward direction.
- FASERν will be centered on the LOS (in the FASER trench) to maximizes fluxes of all neutrino flavors.

F. Kling, Forward Neutrino Fluxes at the LHC, arXiv:2105.08270

Tomoko Ariga: Detecting and studying high-energy neutrinos with FASERν at the LHC
- Emulsion and Timepix detectors exposed to 12 fb\(^{-1}\) in 2018
- Primary goal was to verify muon flux and backgrounds in TI12 & TI18 tunnels
- Secondary goal was to look for neutrinos…
Physics Potential

- Measure neutrino cross-section for all species in collider-energy range (100GeV-TeV)

- FASERν will detect ~10 tau neutrino interactions.
  - Thousands of tau neutrino events possible at HL-LHC, allowing for precision studies of tau neutrino properties
- FASERν will record neutrino interaction event shapes with high precision.
  - This could be useful for validation/tuning of neutrino event generators.
- SM neutrino oscillations are expected to be negligible at FASERν. However, sterile neutrinos with mass ~40eV can cause oscillations.
  - FASERν could act as a short-baseline neutrino experiment.

- The tau neutrino flux small in SM. A new light weakly coupled gauge bosons decaying into tau neutrinos could significantly enhance the tau neutrino flux.
Scattering and Neutrino Detector

- SND@LHC is a compact experiment proposed to make measurements with neutrinos of all three neutrino flavours from the LHC in the pseudo-rapidity range of $7.2 < \eta < 8.6$.
- This range of pseudo-rapidity is currently unexplored, and a large fraction of the corresponding neutrinos originate from charmed-hadron decays.
- Together with the FASERν experiment, SND@LHC will first observe the neutrinos produced by a collider.
- SND@LHC is sensitive to Feebly Interacting Particles (FIP) through scattering off atoms in the detector target.
- The direct-search strategy gives the experiment sensitivity in a region of the FIP mass-coupling parameter space that is complementary to other indirect searches.

**SND Detector**

- Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles.
- **VETO PLANE**: tag penetrating muons.
- **TARGET REGION**: Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection - Scintillating fibers for timing information and energy measurement.
- **MUON SYSTEM**: iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement.
- **Target**: 830 kg of tungsten.
- **Angular acceptance**: $7.2 < \eta < 8.6$, off-axis location.
- **Electromagnetic calorimeter**: $\sim 84X_0$, sampling every $17X_0$.
- **Hadronic calorimeter**: $\sim 10\lambda$ (muon system alone $\sim 8\lambda$), sampling every $\lambda$. 

SND@LHC: Technical Proposal
NEUTRINO EXPECTATIONS

- Expectations in 150 fb-1
- Upward crossing angle
- Neutrino production in LHC pp collisions performed with DPMJET3 embedded in FLUKA
- Particle propagation towards the detector through FLUKA model of LHC accelerator

<table>
<thead>
<tr>
<th>Flavour</th>
<th>Neutrinos in acceptance (E) (GeV)</th>
<th>Yield</th>
<th>CC neutrino interactions (E) (GeV)</th>
<th>Yield</th>
<th>NC neutrino interactions (E) (GeV)</th>
<th>Yield</th>
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<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>145</td>
<td>2.1 x 10^{12}</td>
<td>450</td>
<td>730</td>
<td>480</td>
<td>220</td>
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<tr>
<td>$\bar{\nu}_\mu$</td>
<td>145</td>
<td>1.8 x 10^{12}</td>
<td>485</td>
<td>290</td>
<td>480</td>
<td>110</td>
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<tr>
<td>$\nu_e$</td>
<td>395</td>
<td>2.6 x 10^{11}</td>
<td>760</td>
<td>235</td>
<td>720</td>
<td>70</td>
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<tr>
<td>$\bar{\nu}_e$</td>
<td>405</td>
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<td>680</td>
<td>120</td>
<td>720</td>
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<tr>
<td>$\nu_\tau$</td>
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<td>740</td>
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<tr>
<td>$\bar{\nu}_\tau$</td>
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<td>1.7 x 10^{10}</td>
<td>740</td>
<td>6</td>
<td>740</td>
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<tr>
<td>TOT</td>
<td>4.5 x 10^{12}</td>
<td>1395</td>
<td></td>
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</table>

Neutrinos interacting in SND@LHC
Ideas in view of a future forward facility at HL-LHC

- 2 fully active detectors, both forward but off-axis
- 1: $\eta$ region $\sim 8$
- 2: $\eta$ region $\sim 4.5$
- No shield from other experiments
- Shielded locations (from LHC IP) desirable, similar to T118
- SND2 to be located closer to improve the acceptance (keeping the same $\eta$)