Physics at the Forward Physics Facility.

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Main focus of LHC are heavy particles: Higgs, SUSY … .
Their decay products have high $p_T$ and are distributed almost isotropically.
ATLAS/CMS were constructed to catch them.
Why Forward Physics?

The LHC produces a huge number of hadrons in the forward direction:
$10^{17} \pi^0$, $10^{16} \eta$, $10^{15} D$, $10^{13} B$ within 1 mrad of beam.

Typically low $p_T$ but large energy.

Can we do something with that?
Why Forward Physics?

The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction.
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Why Forward Physics?

These particles escape down the beam pipe and remain undetected.

Indeed, the existing big LHC detectors are perfectly designed NOT to see them.

Central Region
H, SUSY

Forward Region
π, K, D

Light New Physics:
A’, ALPs, DM

SM Physics: νe, νμ, ντ
Why Forward Physics?

LHC tunnel will eventually curve away, but the beam of neutral particles will continue along the beam collision axis.
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Idea: Placed experiment in this beam to detect them.
Experimental Program:
FASER — FASERv — SND@LHC — FPF

Searches for BSM physics:
LLP Decays — DM Scattering — Millicharged Particles

SM Measurements:
Neutrinos — QCD — Cosmic Rays
Location.
Location.
Two new experiments will exploit this potential during run 3 of the LHC: SND@LHC and FASER.
Main Goal: Search for light long-lived particles

pp → LLP + X, LLP travels ~ 480m, LLP → charged tracks + X

Signal is striking:
- highly energetic charged particles (E ~ TeV)
- emerging from an empty decay volume
- point back to the IP through 90 m of rock

Background considerations:
- large flux of muons from the LHC cause muon-associated radiative events
- use scintillators veto to reduce BG to negligible levels
FASER

FASERv
neutrino detector
LOI: 1908.02310
TP: 2001.03073

FASER main detector
LOI: 1811.10243
TP: 1812.09139

1.5 m long
decay volume

2m long
spectrometer

emulsion+target

scintillators

interface tracker

0.6T permanent
magnets

3 tracking stations

ECAL

1 m
FASERv neutrino detector in front of FASER
- 25cm x 25cm x 1.3m, 1.2 ton mass
- placed on axis: $\eta > 9$
- ~10000 neutrinos during LHC Run 3
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Emulsion detectors technology
- used by CHORUS, DONUT, OPERA
- 1000 emulsion films interleaved with 1mm tungsten plates
- global reconstruction with the FASER detector possible
**SND@LHC:** second LHC neutrino experiment

- located on other side of ATLAS
- used emulsion and electronic components
- slightly off-axis location: $7.2 < \eta < 8.7$
- target: 830 kg of tungsten
FASER and SND@LHC are highly constrained by 1980’s infrastructure that was never intended to support experiments.

The proposal: create a dedicated Forward Physics Facility (FPF) for the HL-LHC.
The FPF would house a suite of experiments that will greatly enhance the LHC’s physics potential for **BSM physics searches**, **neutrino physics** and **QCD**.

- **FASER2** magnetized spectrometer for BSM searches
- **FORMOSA** plastic scintillator array for BSM searches
- **AdvSND** electronic neutrino detector
- **FLArE** LAr based neutrino detector
- **FASERv2** emulsion-based neutrino detector
FPF workshop series: 
FPF1, FPF2, FPF3, FPF4

FPF Paper: 
2109.10905  
~75 pages, ~80 authors

Snowmass Whitepaper:  
2203.05090  
~450 pages, ~250 authors
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Motivation: Dark Sectors.
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Simple Model: Dark Matter charged under $U(1)_D$

$$\mathcal{L} \supset -\frac{\epsilon}{2} F^\mu_\nu F'^\mu_\nu - \frac{1}{2} m^2_{A'} A'^2 - m^2_\chi \chi^2 - i g_D A'^2$$

coupling to SM via small mixing with SM photon
dark photon can be massive
massive DM
dark photon couples to DM

SM Sector $\to$ Mediator $\to$ Dark Sector
Motivation: Dark Sectors.

Simple Model: Dark Matter charged under $U(1)_D$

\[ \mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'^2 - m_{\chi}^2 \chi^2 - ig_D A' \chi^2 \]

- Coupling to SM via small mixing with SM photon
- Dark photon can be massive
- Massive DM
- Dark photon couples to DM

Phenomenology depends on masses:

- $m_{A'} > 2m_X$:
  $A' \rightarrow XX$

- $m_{A'} < 2m_X$:
  $A' \rightarrow SM \ SM$
  Long-lived

- $m_{A'} = 0$:
  Milli-charged $X$
Long-Lived Particles: Dark Photon.

parameter space of **visibly** decaying dark photon

displaced decays long-lived particle

prompt decays resonance searches

Kinetic Mixing $\epsilon$

Dark Photon Mass $m_{A'}$ [GeV]
Long-Lived Particles: Dark Photon.
Long-Lived Particles: Dark Photon.

Model predicts DM relic abundance.

DM DD bounds in same model.
Long-Lived Particles: Dark Photon.
Long-Lived Particles: Dark Higgs.

Dark Higgs = light scalar mixing with SM Higgs:  \[ \mathcal{L} \supset m_\phi^2 \phi^2 + \sin \theta y_f \phi \bar{f} f \]

mainly produced in B and K decays

FASER sensitivity

other proposed experiments
Long-Lived Particles: Dark Higgs.

- \( \phi \) as DM
  - [Feng et al: 1710.09387]

- \( \phi \) as relaxion
  - [Winkler: 1809.01876]

- \( \phi \) as inflaton
  - [Bramante et al: 1608.08625]
  - [Okada, Raut: 1910.09663]

- \( \phi \) and NS mergers
  - [Dev et al: 2111.05852]
Long-Lived Particles.

For details on many more models see 1811.12522 and 2203.05090.
Dark Matter Scattering.

if \( m_{A'} > 2m_X \): \( A' \) decays to DM \( \rightarrow \) LHC produces energetic DM beam

[Batell et al: 2101.10338]

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parameter space of **invisibly** decaying dark photon

DM scatters in neutrino detector: \( X_e \rightarrow X_e \).
If $m\Lambda'=0$: $X$ is effectively milli-charged with $Q=\varepsilon e$
If $mA' = 0$: $X$ is effectively milli-charged with $Q = \varepsilon e$

flux is $\sim 100$ times larger in forward direction

**FORMOSA**

[Foroughi-Abari et al: 1910.09663]
If $m_{A'=0}$, $X$ is effectively milli-charged with $Q=\epsilon e$ 

$mCP$ explaining EDGES anomaly

[Liu et al: 1908.06986]
Searches for BSM Physics

dark sector searches

production

scattering

low $dE/dx$

curved tracks

decays

neutrinos

production

oscillation

MDM

self-interaction

NSI

BSM neutrino physics
Experimental Program:
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Neutrinos at the LHC.

There is a huge flux of neutrinos in the forward direction, mainly from π, K and D meson decays. [De Rujula et al. (1984)]

In 2018, the FASER collaboration placed ~30 kg pilot emulsion detectors in T118 for a few weeks. First neutrino interaction candidates were reported. [FASER, 2105.06197]
Neutrinos at the LHC.

FASER Pilot Detector
lunchbox-size, 4 weeks
$0 (recycled parts)
6 neutrino interaction candidates

all previous collider detectors
building-size, decades ∼$1B
0 neutrino interaction candidates

slide by Jonathan Feng
Neutrinos at the LHC.
LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.
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FASERv and SND@LHC will detect O(10k) neutrinos.
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Proposed FPF experiment have potential to detect $O(1M)$ neutrinos.
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Neutrinos at the LHC.

two applications from: PHENO2022

hadronic resonances in $\nu$-$e$ scattering

Vedran Brdar’s talk on Tuesday

[Brdar et al: 2112.03283]

Neutrino electromagnetic properties

Roshan Mammen Abraham's talk on Monday

[Ismail et al: 2012.10500], [Ismail et al: 2109.05032]
Where do the LHC neutrinos come from?

LHC neutrinos = probe of forward particle production
Forward Particle Production

- Intrinsic charm
- Charm fragmentation
- Large $x$ PDFs: $x \sim 1$
- BFKL dynamics
- Ultra low-$x$ PDFs: $x \sim 10^{-7}$
- Color glass condensate
- Forward charm

QCD
Forward Particle Production

- **large x PDFs**: $x \sim 1$
- **intrinsic charm**
- **charm fragmentation**
- **BFKL dynamics**
- **ultra low-x PDFs**: $x \sim 10^{-7}$
- **color glass condensate**

**TeV Energy Neutrino Interaction**

- **neutrino DIS at TeV scale**
- **color transparency**
- **hadronization in nuclear medium**
- **strangeness**
- **nuclear PDFs**
- **shadowing**
- **EMC effect**
forward charm production at the LHC

constraints on prompt atmospheric neutrino flux at IceCube

Astroparticle Physics.

cosmic ray muon puzzle:
observed excess of muons compared to hadronic interaction models

forward pion/kaons fluxes will provide crucial input

Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660
FASER and SND@LHC will soon start to take data in LHC’s forward direction.

The FPF is proposed to continue this program during the HL LHC era.

Significant extension of the LHC’s physics program.

We invite the Pheno community to participate in this program. You are welcome to join!
Backup.
Neutrino Fluxes and Rates.

Event rates at LHC neutrino experiments estimated with two LO MC generators: SIBYLL / DPMJET

<table>
<thead>
<tr>
<th>Detector</th>
<th>Number of CC Interactions</th>
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<tbody>
<tr>
<td></td>
<td>$\nu_e + \bar{\nu}_e$</td>
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<tr>
<td><strong>LHC Run3</strong></td>
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<tr>
<td>FASER$\nu$</td>
<td>1 ton</td>
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<tr>
<td>SND@LHC</td>
<td>800kg</td>
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<tr>
<td><strong>HL-LHC</strong></td>
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<tr>
<td>FASER$\nu$2</td>
<td>20 tons</td>
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<tr>
<td>FLArE</td>
<td>10 tons</td>
</tr>
<tr>
<td>AdvSND</td>
<td>2 tons</td>
</tr>
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Large spread in current generator predictions

**Challenge:**
For neutrino physics measurement we need to quantify and reduce neutrino flux uncertainties

**Opportunity:**
Forward neutrino flux measurement can help to improve our understanding of underlying physics.
Forward particle production is poorly constrained by other LHC experiments. LHC neutrinos fluxes measurement will provide novel complimentary information.

**pions & kaons:** nonperturbative QCD $\rightarrow$ improve MC generators

**charm:** perturbative QCD $\rightarrow$ test BFKL dynamics, constrain low-x PDFs, probe gluon saturation and intrinsic charm