Lecture 3: Neutrino Measurements

October 21th 2022
Felix Kling
The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

$10^{17} \pi^0, 10^{16} \eta, 10^{15} D, 10^{13} B$ within 1 mrad of beam

Can we do something with that?

**Light New Physics:**
A', ALPs, DM

**Central Region**
H, t, SUSY

**SM Physics:** $v_e, v_\mu, v_\tau$

**Forward Region**
$\pi, K, D$
Motivation
Collider Neutrinos

- neutrinos detected from many sources, but not from colliders
First Collider Neutrinos

There is a huge flux of neutrinos in the forward direction, mainly from $\pi$, $K$ and $D$ meson decays.

[De Rujula et al. (1984)]
First Collider Neutrinos

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[De Rujula et al. (1984)]

In 2018, the FASER collaboration placed $\sim$30 kg pilot emulsion detectors in TI18 for a few weeks.
First neutrino interaction candidates were reported.  
[FASE, 2105.06197]
First Collider Neutrinos
FIG. 4. Monte Carlo simulation distributions of the BDT input variables for the neutrino signal and neutral hadron background. The observed neutral vertices in the data sample are shown in black. The Monte Carlo simulation distributions are normalized to 12.2 fb$^{-1}$. 

First Collider Neutrinos
FIG. 6. The BDT outputs of the observed neutral vertices, and the expected signal and background distributions (stacked) fitted to data. Higher BDT output values are associated with neutrino-like vertex features.
First Collider Neutrinos

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

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

slide by Jonathan Feng
Collider Neutrinos
Collider Neutrinos

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.
Collider Neutrinos

LHC provides a **strongly collimated** beam of **TeV energy** neutrinos of all three flavours in the far forward direction.

FASERv and SND@LHC will detect $\mathcal{O}(10k)$ neutrinos.
Collider Neutrinos

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.

FASERv and SND@LHC will detect $O(10k)$ neutrinos.

Proposed FPF experiment have potential to detect $O(1M)$ neutrinos.
Neutrino Fluxes and Interaction
Collider Neutrinos

energy spectrum of interacting neutrinos

neutrino flux as function of displacement from LoS

100 GeV - few TeV energies

flux peaked around LoS, start to drop around 1m away from LoS

complementary coverage of FASERv and SND@LHC
### Event Rates

<table>
<thead>
<tr>
<th>Generators</th>
<th>FASERν</th>
<th>SND@LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>light hadrons</td>
<td>heavy hadrons</td>
<td></td>
</tr>
<tr>
<td>SIBYLL</td>
<td>SIBYLL</td>
<td>1501</td>
</tr>
<tr>
<td>DPMJET</td>
<td>DPMJET</td>
<td>5761</td>
</tr>
<tr>
<td>EPOS LHC</td>
<td>Pythia8 (Hard)</td>
<td>2521</td>
</tr>
<tr>
<td>QGSJET</td>
<td>Pythia8 (Soft)</td>
<td>1616</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combination (all)</th>
<th>FASERν</th>
<th>SND@LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>νₑ + ¯νₑ</td>
<td>2850</td>
<td>1651</td>
</tr>
<tr>
<td>νₑ + ¯νₑ</td>
<td>9636</td>
<td>1516</td>
</tr>
<tr>
<td>νₑ + ¯νₑ</td>
<td>408</td>
<td>1516</td>
</tr>
<tr>
<td>νₑ + ¯νₑ</td>
<td>1880</td>
<td>1626</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combination (w/o DPMJET)</th>
<th>FASERν</th>
<th>SND@LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>νₑ + ¯νₑ</td>
<td>9636</td>
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**TABLE II.** Expected number of charged current neutrino interaction events occurring in FASERν and SND@LHC during LHC Run 3 with 250 fb⁻¹ integrated luminosity. Here we assume a target mass of 1.2 tons for FASERν and 800 kg for SND@LHC; further details on the experimental setup are provided in ???. We provide predictions for SIBYLL 2.3d, DPMJET III.2017.1, EPOS LHC/Pythia 8.2 with HardQCD, and QGSJET II-04/Pythia 8.2 with SoftQCD. The two bottom rows provide a combined average, both including and excluding the DPMJET prediction, where the uncertainties correspond to the range of predictions obtained from different MC generators.
Where do neutrinos come from?
Neutrinos from Light Hadron Decays

Two issues to consider

**Event Generation**

Light hadron production cannot be described by perturbative QCD. Instead, one has to use hadronic interaction models / MC generators.

**Particle Propagation**

Light hadron (pions, kaons, hyperons) are long-lived. So one need to model their propagation, absorption and decays in the LHC infrastructure.
Neutrinos from Light Hadron Decays

Typical generators from cosmic ray physics: EPOS, QGSJET, SIBYLL, DMPJET, (Pythia)

Some guidance by data: forward photon at LHCf [1703.07678]
Neutrinos from Light Hadron Decays

This has been realized as fast neutrino flux simulation implemented as RIVET module. [Kling, 2105.08270]
Neutrinos from Light Hadron Decays
Charm production can (in principle) be described by perturbative QCD: $g \, g \rightarrow c \, c$

$$d\sigma(pp\rightarrow D + X) = f_g(x_1)f_g(x_2) \times d\sigma(gg\rightarrow c + X) \times F(c\rightarrow D)$$

hadronic cross section  
PDF  
partonic cross section  
hadronization

Some guidance by data: D-meson spectra by LHCb [1510.01707]
Neutrinos from Charm Decay

First estimate at NLO by Bai et al: 2002.03012

\[ \sqrt{s} = 13 \text{ TeV}, \quad \langle k_T \rangle = 2.2 \text{ GeV} \]

\[ 2.0 < y < 2.5 \text{ (m=0)} \]
\[ 2.5 < y < 3.0 \text{ (m=2)} \]
\[ 3.0 < y < 3.5 \text{ (m=4)} \]
\[ 3.5 < y < 4.0 \text{ (m=6)} \]
\[ 4.0 < y < 4.5 \text{ (m=8)} \]

\[ d^2\sigma/(dp_T dy) \text{ [\mu b/(GeV)]} \]

\[ dN/dE \text{ [GeV}^{-1} \text{ ton}^{-1}] \]

\[ \sqrt{s} = 14 \text{ TeV}, \quad \eta > 6.87 \]
\[ L_{\text{tot}} = 3000 \text{ fb}^{-1} \]
\[ (\mu_R, \mu_F) = (1, 1.5) m_T \]

\[ \nu_\tau + \bar{\nu}_\tau \]

uncertainty band: vary scales by factor two
Neutrinos from Charm Decay

Estimate based on different approaches (NLO collinear and kT factorization) by Bhattacharya, Kling, Sarcevic and Stasto: 2203.05090
Neutrinos from Charm Decay

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

<table>
<thead>
<tr>
<th>Detector</th>
<th>Name</th>
<th>Mass</th>
<th>Coverage</th>
<th>Number of CC Interactions</th>
<th>Number of CC Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\nu_e + \bar{\nu}_e$</td>
<td>$\nu_{\mu} + \bar{\nu}_{\mu}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\nu_\tau + \bar{\nu}_\tau$</td>
<td>$\nu_\tau + \bar{\nu}_\tau$</td>
</tr>
<tr>
<td>LHC Run3</td>
<td>FASER(\nu)</td>
<td>1 ton</td>
<td>$\eta \gtrsim 8.5$</td>
<td>1.3k / 4.6k</td>
<td>6.1k / 9.1k</td>
</tr>
<tr>
<td></td>
<td>SND@LHC</td>
<td>800kg</td>
<td>$7 &lt; \eta &lt; 8.5$</td>
<td>180 / 500</td>
<td>1k / 1.3k</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>FASER(\nu)_2</td>
<td>20 tons</td>
<td>$\eta \gtrsim 8$</td>
<td>178k / 668k</td>
<td>943k / 1.4M</td>
</tr>
<tr>
<td></td>
<td>FLArE</td>
<td>10 tons</td>
<td>$\eta \gtrsim 7.5$</td>
<td>36k / 113k</td>
<td>203k / 268k</td>
</tr>
<tr>
<td></td>
<td>AdvSND</td>
<td>2 tons</td>
<td>$7.2 \lesssim \eta \lesssim 9.2$</td>
<td>6.5k / 20k</td>
<td>41k / 53k</td>
</tr>
</tbody>
</table>

Large spread in 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.
Neutrino Interactions

for $E_{\nu} > 100\text{GeV}$: deep inelastic scattering (DIS) $q\nu \rightarrow q'\ell$

\[
\frac{d\sigma_{\nu p}}{dx \, dy} = \frac{G_F^2 m_p E_{\nu}}{\pi} \frac{m_{W,Z}^4}{(Q^2 + m_{W,Z}^2)^2} \times \left[ x f_q(x, Q^2) + x f_{\bar{q}}(x, Q^2)(1 - y)^2 \right]
\]

* cross section grows linear with energy: $\sigma \sim E$

* proton momentum carried by the quark $q$: $x \sim 0.1$

* fraction of the neutrino energy transferred: $y \sim 0.5$

* transferred four-momentum: $Q^2 \sim (10 \text{ GeV})^2$
Physics Potential
Overview

- **neutrino production**
- **neutrino propagation**
- **neutrino interactions**

**Forward Particle Production**

**LHC as Short Baseline Neutrino Experiment**

**TeV-energy Neutrino Interaction**

**pp-collision**

**ATLAS IP**

- deflected charged particles
- LHC magnets
- LHC tunnel
- LHCv

- ~100m rock

**neutrino**

**propagation**

**interaction**
Forward Particle Production

Where do the LHC neutrinos come from?

LHC neutrinos = probe of forward particle production
QCD - Overview

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

Forward Particle Production
QCD - Overview

Forward Particle Production

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

TeV Energy Neutrino Interaction

- neutrino DIS at TeV scale
- color transparency
- hadronization in nuclear medium
- strangeness
- nuclear PDFs
- shadowing
- EMC effect

$^{184}_W$
QCD with charm production

Neutrinos from charm decay could allow to test transition to small-x factorization and constrain low-x gluon PDF.
QCD with charm production

Gluon saturation
Bhattacharya, Kling, Sarcevic and Stasto: (unpublished)

LHCb 13 TeV: $D_0 + \bar{D}_0$

FLARE 13 TeV: $\nu_e + \bar{\nu}_e$
QCD with charm production

Intrinsic Charm (IC)
- charm in pQCD mainly via gluon scattering
- possible non–perturbative component to charm PDF: IC
- leads to forward, high-xF charm production
- not observed experimentally, existence is controversial

![Graph showing CT14 IC parametrizations, Q = 2 GeV]
QCD with charm production

Intrinsic Charm
Goncalves, Maciula, Szczurek: 2210.08890
QCD - Neutrino Scattering

DIS neutrino interactions $\nu_\mu \, q \rightarrow \mu \, q'$ can be used to probe PDFs.

$$
\frac{d\sigma_{\nu p}}{dx \, dy} = \frac{G_F^2 \, m_p \, E_\nu}{\pi} \frac{m_{W,Z}^4}{(Q^2 + m_{W,Z}^2)^2} \times \left[ x f_q(x, Q^2) + x f_\bar{q}(x, Q^2)(1 - y)^2 \right]
$$

LHC Neutrino experiments can measure
- the muon charge $q_\mu$
- the muon energy $E_\mu$,
- the neutrino energy $E_\nu$
- the muon angle $\theta_\mu$

This allows to reconstruct the DIS variables
- $Q = E_\mu \, \theta_\mu$,
- $y = 1 - E_\mu / E_\nu$,
- $x = Q^2 / (2 \, E_\nu \, M \, y)$
QCD - Neutrino Scattering

Nuclear effects

(anti-)strange quark PDF using $\nu s \rightarrow \ell c$
forward charm production at the LHC

constraints on prompt atmospheric neutrino flux at IceCube

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
BSM Physics Searches

dark sector searches

production
scattering
low dE/dx
curved tracks
decays

LLPs, MCPs, DM ...

neutrinos

production
oscillation
MDM
self-interaction
NSI

BSM neutrino physics
BSM Physics Searches

Sterile Neutrino Oscillations: 2109.10905

![Graph showing 95% CL Sensitivity with Expected, ±1 σ, ±2 σ, and Global Constraint](image)

Neutrinophilic mediators: 2111.05868

![Graph showing coupling g_8 vs Gauge Boson Mass m_ν = 3m_μ [GeV]](image)

dark sectors: 2111.10343

![Graph showing U(1)_α - ν_τ + DM (q_α=3)](image)

Neutrino electromagnetic properties

![Graph showing events vs m_ν vs E_r](image)
Backup
Angular / Rapidity Distribution

[Graph showing angular and rapidity distributions with various event types and models.]
Collider Neutrinos

energy spectrum of interacting neutrinos

neutrino flux as function of displacement from LoS

100 GeV - few TeV energies

flux peaked around LoS, start to drop around 1m away from LoS

complementary coverage of FASERν and SND@LHC