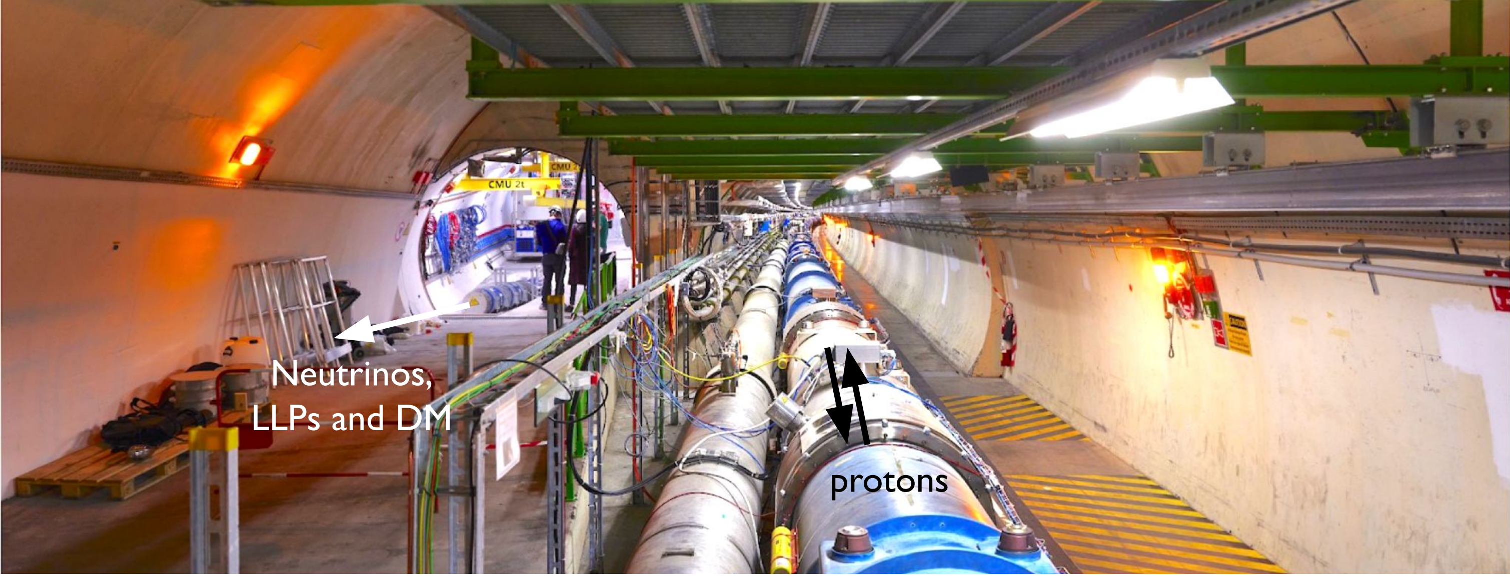


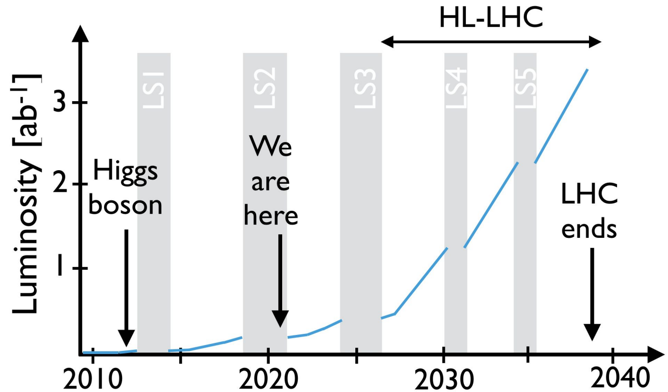
Looking Forward to New Physics at the LHC.

Felix Kling

Anomalies 2021

11/12/2021

Motivation.



The LHC will soon start to prepare for its high-luminosity phase.

Is there anything we miss?
Can we do something to enhance its physics potential?

If yes, we need to do it now or lose them for many decades.

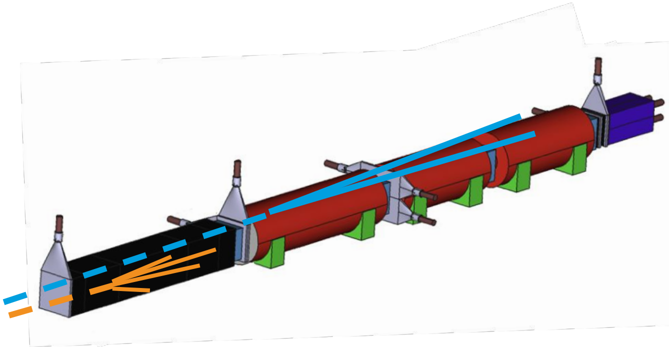
Proposal: Explore a rich BSM and SM physics program in the far forward region to greatly expands the LHC physics potential.

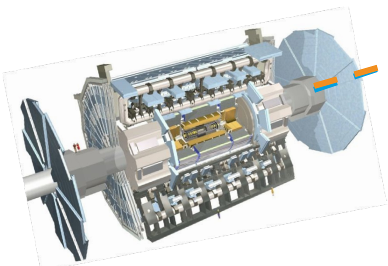
Motivation.

Light hadrons are copiously produced in the far-forward direction of LHC:
4·10^17 π0, 6·10^16 η, 2·10^15 D, 10^13 B within 2mrad of beam

Searches for New Physics:

* light LLPs: A', S, ALPs, HNLs, iDM, …
* produced via π0→γA', D→KℓN, B→X_sS,
* lifetime ~ 500m





SM Measurements:

* pp collision produce forward neutrino beam
* produced via π→νμ, K→νe, D→ντ
* TeV energies

Experimental Program:
FASER - FASERν - FPF

Searches for BSM physics:
LLPs - DM - mCPs

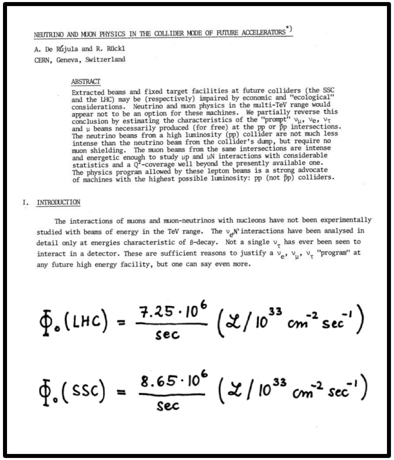
SM Measurements:
Neutrinos - QCD - Cosmic Rays

Neutrinos at the LHC.

Neutrinos detected from many sources,
but not from colliders.

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

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



NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

A. De Rújula and R. Rückl
CERN, Geneva, Switzerland

ABSTRACT

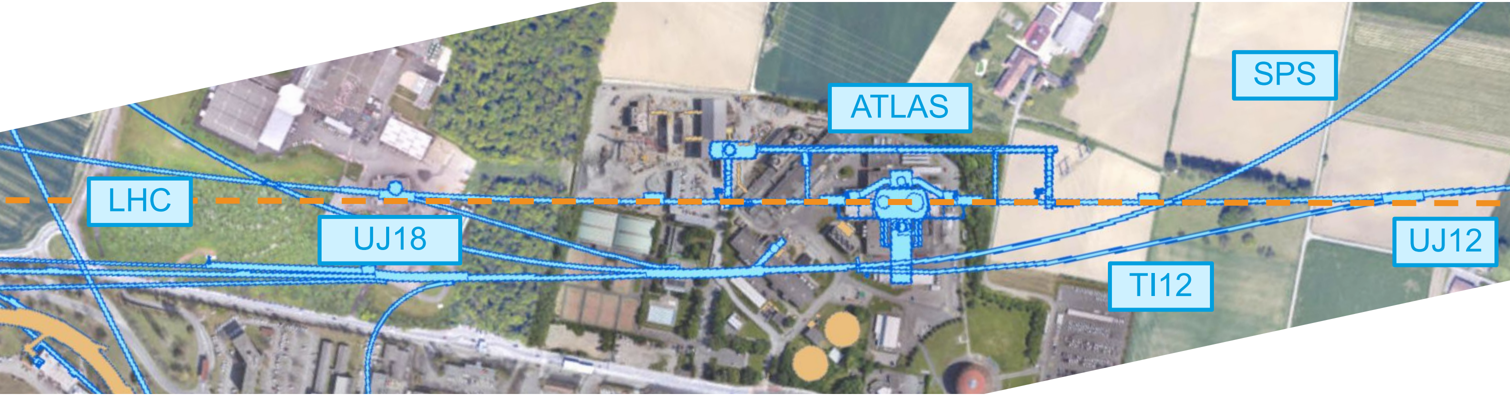
Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.

I. INTRODUCTION

The interactions of muons and muon-neutrinos with nucleons have not been experimentally studied with beams of energy in the TeV range. The $\nu_e N$ interactions have been analysed in detail only at energies characteristic of β-decay. Not a single ν_τ has ever been seen to interact in a detector. These are sufficient reasons to justify a ν_e, ν_μ, ν_τ "program" at any future high energy facility, but one can say even more.

$$\Phi_0(LHC) = \frac{7.25 \cdot 10^6}{sec} \left(\mathcal{L} / 10^{33}\ cm^{-2} sec^{-1} \right)$$

$$\Phi_0(SSC) = \frac{8.65 \cdot 10^6}{sec} \left(\mathcal{L} / 10^{33}\ cm^{-2} sec^{-1} \right)$$

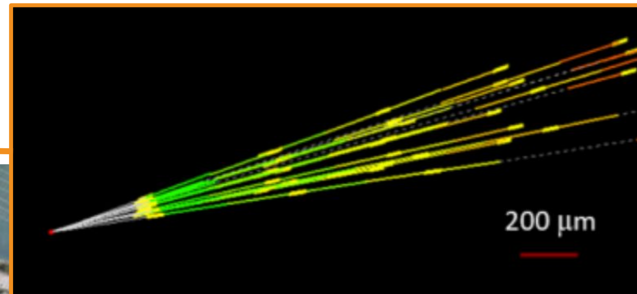


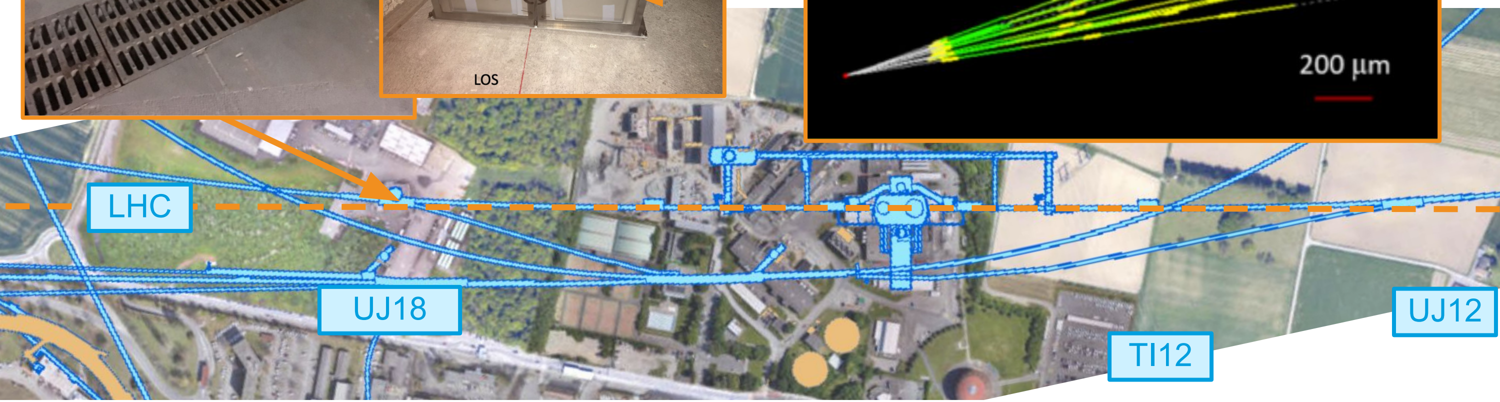
First Neutrino Candidates.

In 2018, the FASER collaboration placed ~30 kg pilot emulsion detectors in TI18 for a few weeks. O(10) neutrino interactions expected

First neutrino interaction candidates were recently reported.

[FASER, 2105.06197]



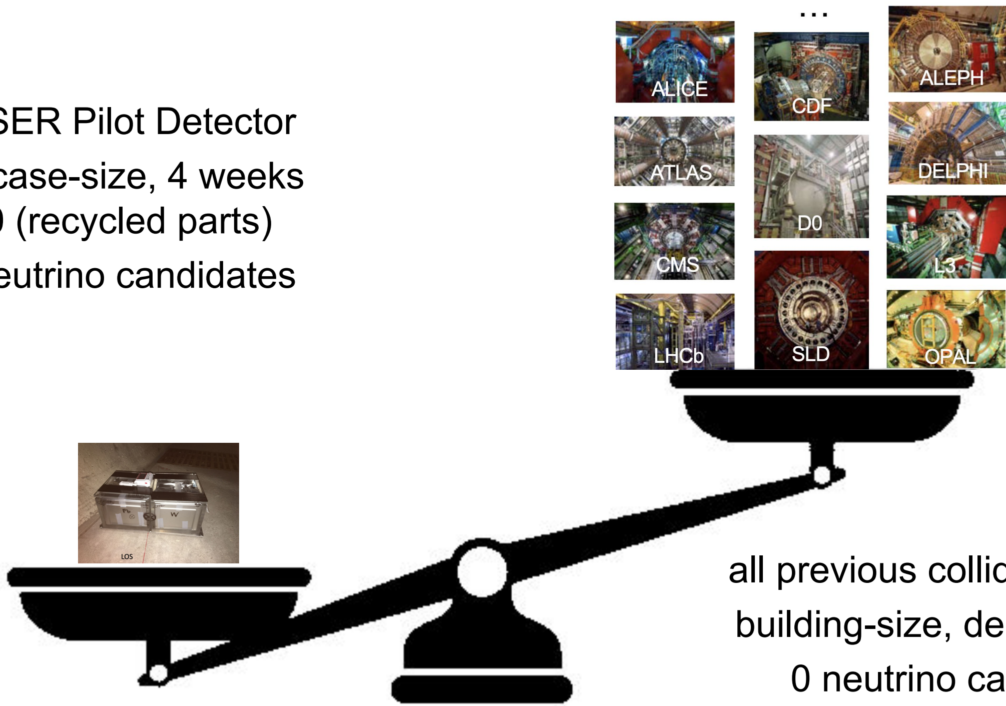


First Neutrino Candidates.

FASER Pilot Detector

suitcase-size, 4 weeks
$0 (recycled parts)

6 neutrino candidates

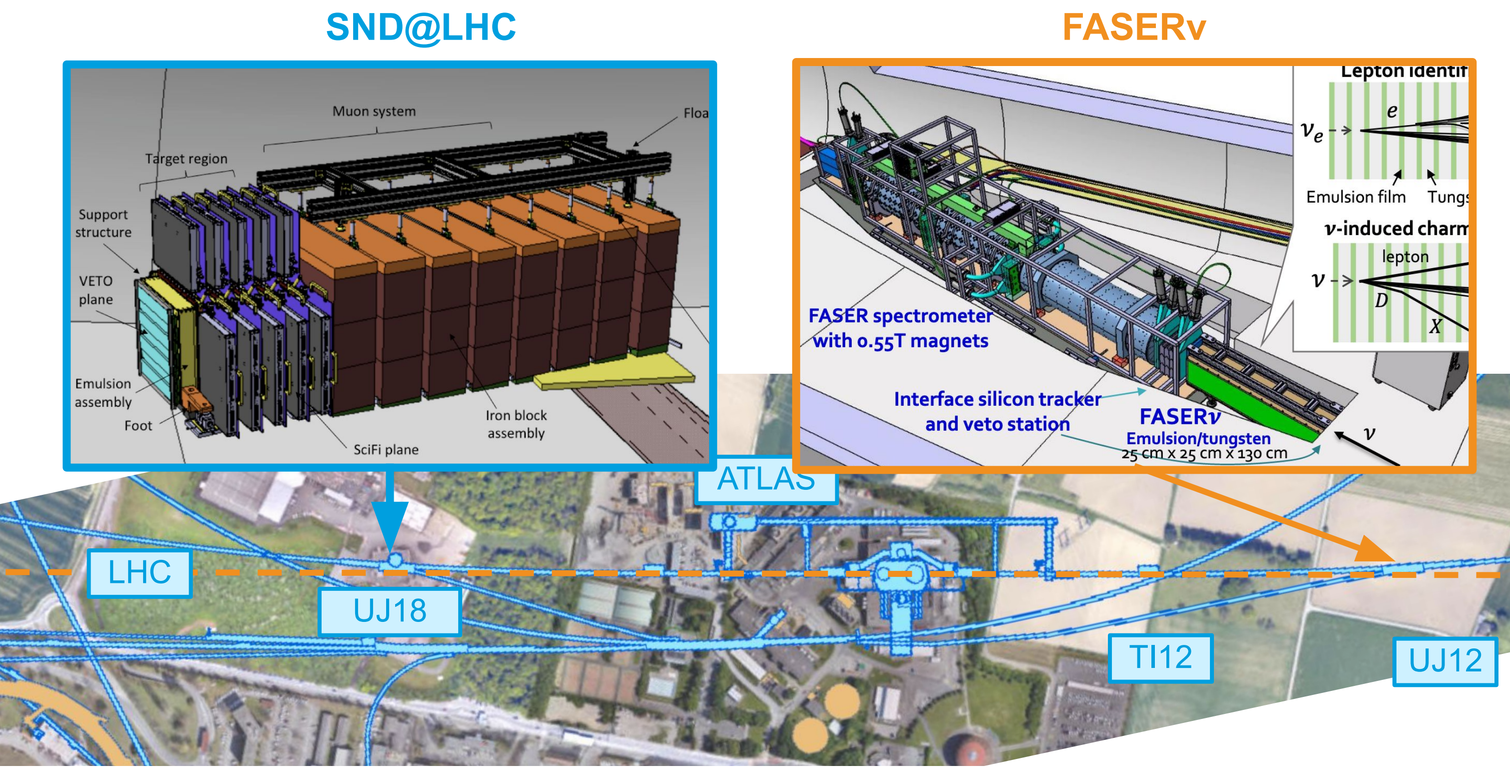


all previous collider detectors
building-size, decades ~$1B
0 neutrino candidates

slide by Jonathan Feng

New LHC Experiments during Run 3.

During Run 3 of the LHC, two new experiments will detect LHC neutrinos



New LHC Experiments during Run 3.

FASER main detector

LOI: 1811.10243

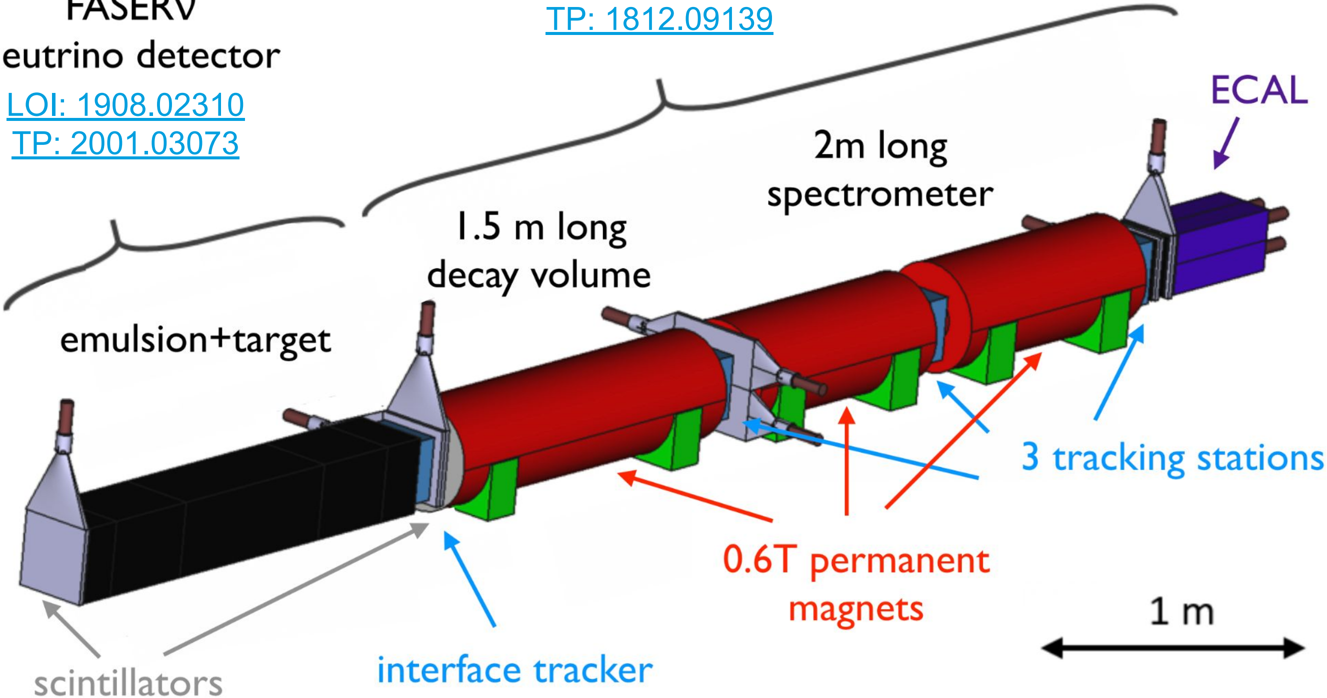
TP: 1812.09139

FASERν

neutrino detector

LOI: 1908.02310

TP: 2001.03073



New LHC Experiments during Run 3.

Thanks to the generous funding by the Heising-Simons Foundation, the Simons Foundation and CERN

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

CERN

08/2017: Idea

03/2019: Approval and Funding

PHYSICS TODAY

A small detector could strike big in the search for dark matter

Low cost, spare parts, private money, and further serendipity converged to accelerate a new experiment at the LHC.

Toni Feder

FASER: CERN approves new experiment to look for long-lived, exotic particles

The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021

7 MARCH, 2019 | By Cristina Agrigoroae

2020/2021: Construction

CERN Bulletin

Issue No. 12-13/2021 · Thursday 25 March 2021

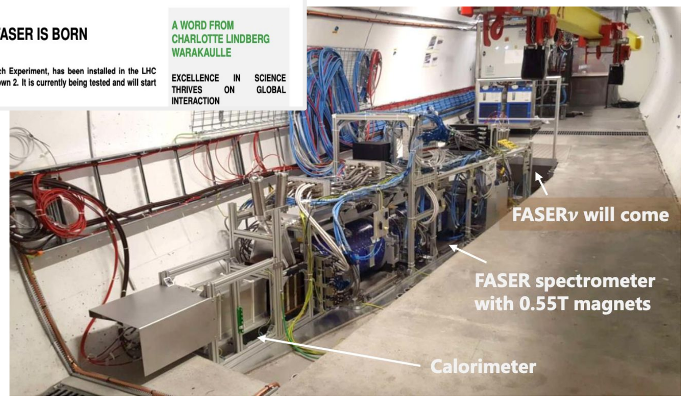
More articles at: http://home.cern/cern-people

LS2 REPORT: FASER IS BORN

FASER, the Forward Search Experiment, has been installed in the LHC tunnel during Long Shutdown 2. It is currently being tested and will start taking data next year

A WORD FROM CHARLOTTE LINDBERG WARAKAULLE

EXCELLENCE IN SCIENCE THRIVES ON GLOBAL INTERACTION



2022-2024: Operation

FASER

77 collaborators
21 institutions
9 countries

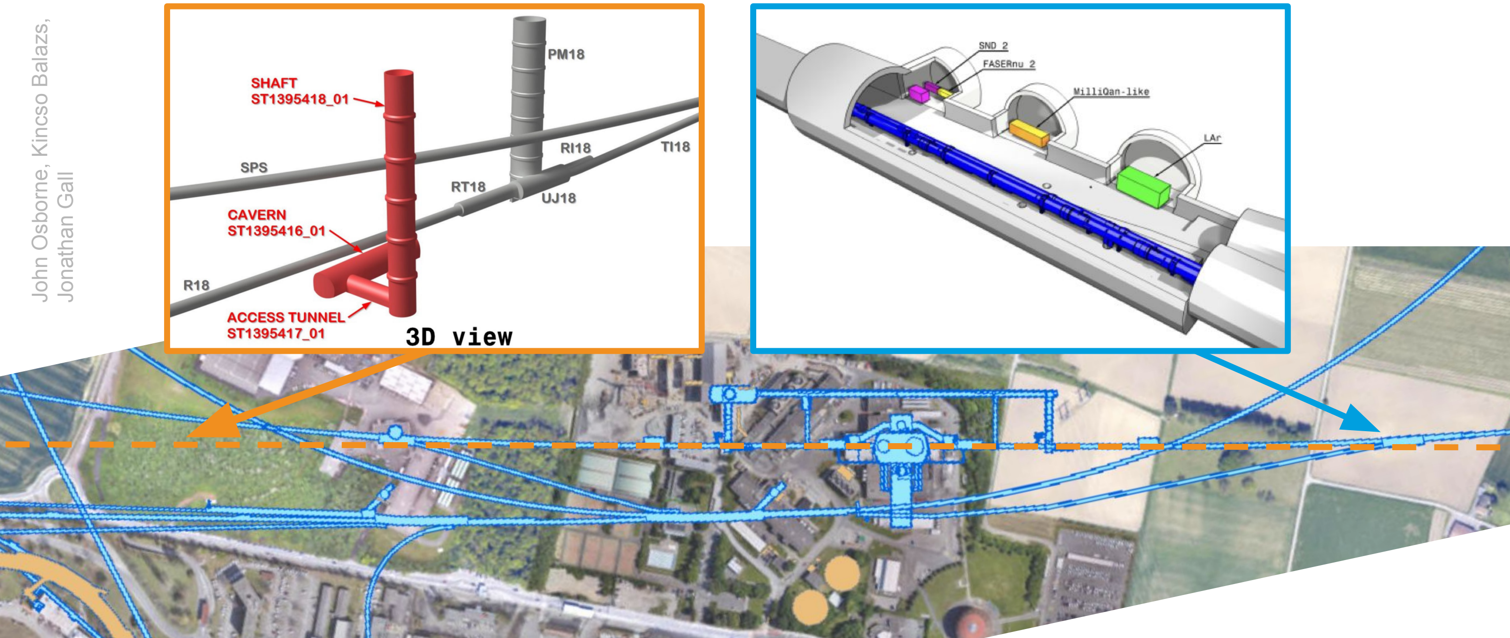
Example: Neutrinos at the LHC.

FASER and SND@LHC are currently highly constrained by 1980's infrastructure that was never intended to support experiments

The proposal: create a Forward Physics Facility (FPF) for the HL-LHC to house a suite of experiments. Two promising locations were identified.

Purpose Built Facility

UJ12 Alcove Extension



John Osborne, Kincso Balazs, Jonathan Gall

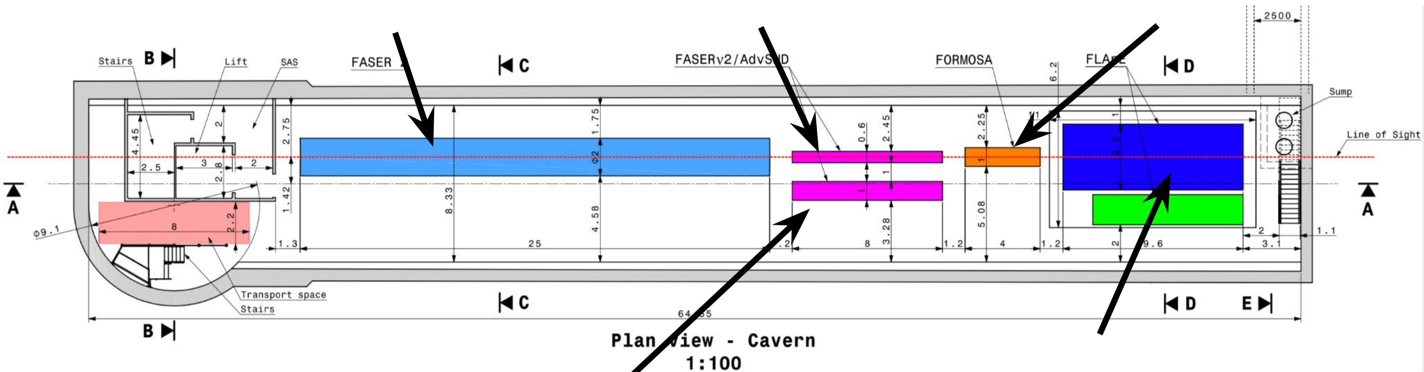
Forward Physics Facility.

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

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches



AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

Forward Physics Facility.

Three dedicated FPF workshops:
November 2020: https://indico.cern.ch/event/955956
May 2021: https://indico.cern.ch/event/1022352
October 2021: https://indico.cern.ch/event/1076733/

Results summarized in paper discussing the facility, proposed experiments and physics potential for BSM Physics, Neutrinos, QCD and Astroparticle Physics.

~75 pages, written over last ~3month by ~80 authors

arXiv: 2109.10905

The Forward Physics Facility:
Sites, Experiments, and Physics Potential

Luis A. Anchordoqui,[1,*] Akitaka Ariga,[2,3] Tomoko Ariga,[4] Weidong Bai,[5] Kincso Balazs,[6] Brian Batell,[7] Jamie Boyd,[6] Joseph Bramante,[8] Adrian Carmona,[9] Mario Campanelli,[10] Francesco G. Celiberto,[11,12,13] Grigorios Chachamis,[14] Matthew Citron,[15] Giovanni De Lellis,[16,17] Albert de Roeck,[6] Hans Dembinski,[18] Peter B. Denton,[19] Antonia Di Crecsenzo,[16,17,6] Milind V. Diwan,[20] Liam Dougherty,[21] Herbi K. Dreiner,[22] Yong Du,[23] Rikard Enberg,[24] Yasaman Farzan,[25] Jonathan L. Feng,[26,†] Max Fieg,[26] Patrick Foldenauer,[27] Saeid Foroughi-Abari,[28] Alexander Friedland,[29,*] Michael Fucilla,[30,31] Jonathan Gall,[32] Maria Vittoria Garzelli,[33,‡] Francesco Giuli,[34] Victor P. Goncalves,[35] Marco Guzzi,[36] Francis Halzen,[37] Juan Carlos Helo,[38,39] Christopher S. Hill,[40] Ahmed Ismail,[41,*] Ameen Ismail,[42] Sudip Jana,[43] Yu Seon Jeong,[44] Krzysztof Jodłowski,[45] Fnu Karan Kumar,[20] Kevin J. Kelly,[46] Felix Kling,[29,47,§] Rafał Maciuła,[48] Roshan Mammen Abraham,[41] Julien Manshanden,[33] Josh McFayden,[49] Mohammed M. A. Mohammed,[30,31] Pavel M. Nadolsky,[50,*] Nobuchika Okada,[51] John Osborne,[6] Hidetoshi Otono,[4] Vishvas Pandey,[52,46,*] Alessandro Papa,[30,31] Digesh Raut,[53] Mary Hall Reno,[54,*] Filippo Resnati,[6] Adam Ritz,[28] Juan Rojo,[55] Ina Sarcevic,[56,*] Christiane Scherb,[57] Pedro Schwaller,[58] Holger Schulz,[59] Dipan Sengupta,[60] Torbjörn Sjöstrand,[61,*] Tyler B. Smith,[26] Dennis Soldin,[53,*] Anna Stasto,[62] Antoni Szczurek,[48] Zahra Tabrizi,[63] Sebastian Trojanowski,[64,65] Yu-Dai Tsai,[26,46] Douglas Tuckler,[66] Martin W. Winkler,[67] Keping Xie,[7] and Yue Zhang[66]

The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era. Located along the beam collision axis and shielded from the interaction point by at least 100 m of concrete and rock, the FPF will house experiments that will detect particles outside the acceptance of the existing large LHC experiments and will observe rare and exotic processes in an extremely low-background environment. In this work, we summarize the current status of plans for the FPF, including recent progress in civil engineering in identifying promising sites for the FPF; the FPF experiments currently envisioned to realize the FPF's physics potential; and the many Standard Model and new physics topics that will be advanced by the FPF, including searches for long-lived particles, probes of dark matter and dark sectors, high-statistics studies of TeV neutrinos of all three flavors, aspects of perturbative and non-perturbative QCD, and high-energy astroparticle physics.

Experimental Program:
FASER - FASERν - FPF

Searches for BSM physics:
LLPs - DM - mCPs

SM Measurements:
Neutrinos - QCD - Cosmic Rays

Motivation: Dark Sectors.

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

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

coupling to SM via small mixing with SM photon

massive gauge boson: dark photon

dark photon couples to DM

Dark Matter Scattering.

mA’ > 2mX

↓

dark photon promptly decays in DM

↓

LHC produces DM beam

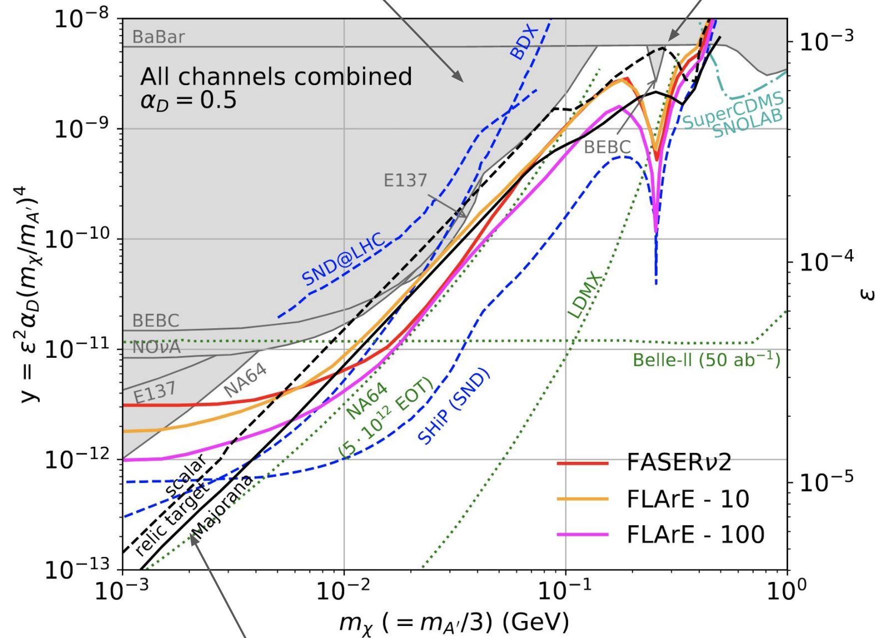
↓

DM scattering in neutrino detector

for more details see: [2101.10338](2101.10338)

existing constraints

A’ mixes resonantly with ω meson



where we would expect DM in this model

Long-Lived Particles.

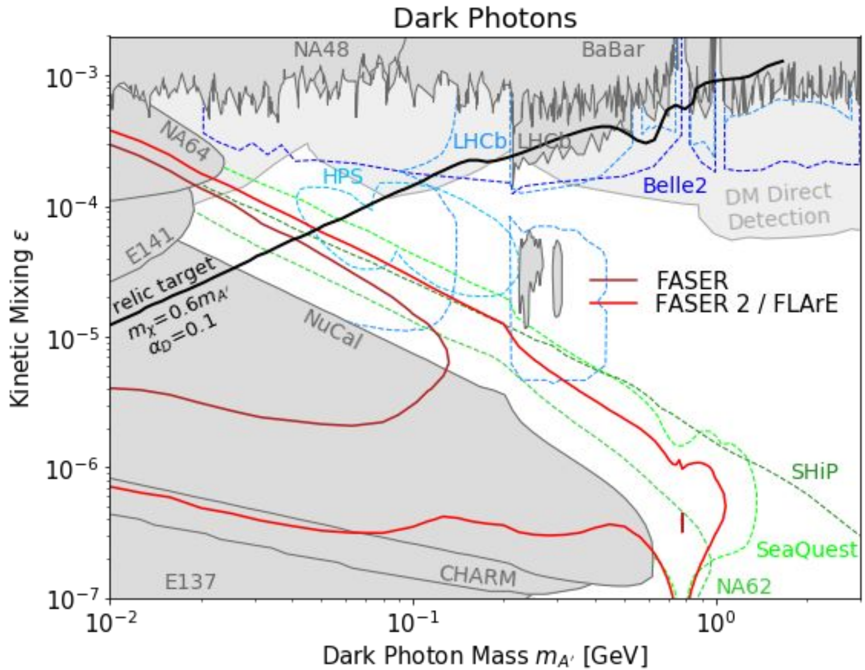
If mA’ < 2mX

↓

A’ decays to SM particles

↓

Long lived particle decays

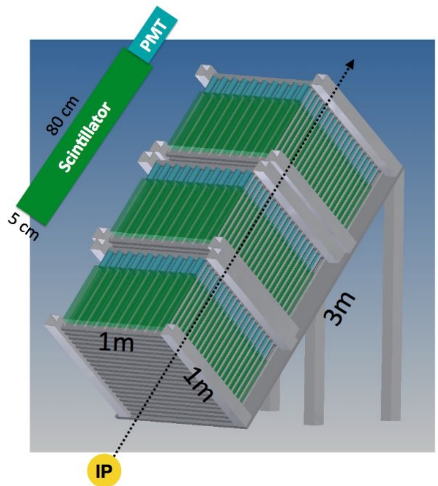


For details and many more models see [1811.12522](1811.12522).

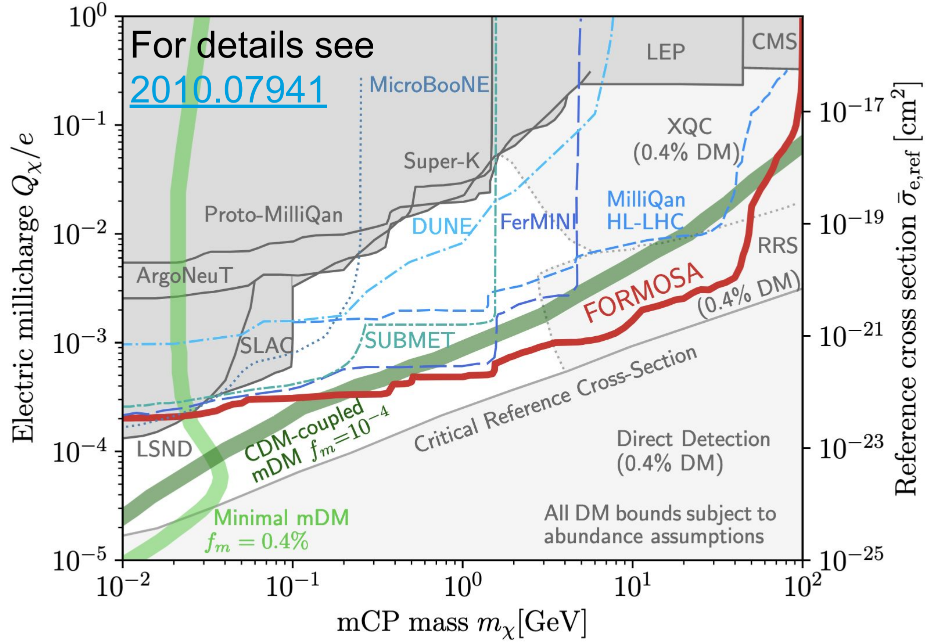
MilliCharged Particles.

If mA'=0: X is effectively milli-charged with Q=εe → search for minimum ionizing particle with very small dE/dx

MilliQan was proposed as dedicated LHC experiment to search for MCPs near CMS. But it was noted that sigal flux is ~100 times larger in forward direction.

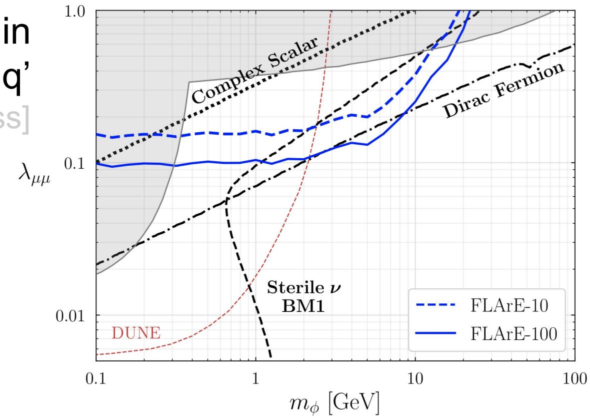


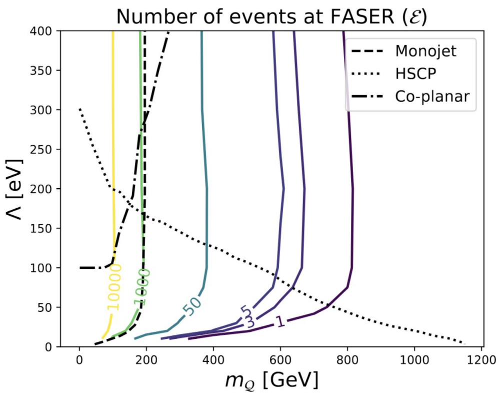
milliQan detector: 1607.04669



More Ideas.

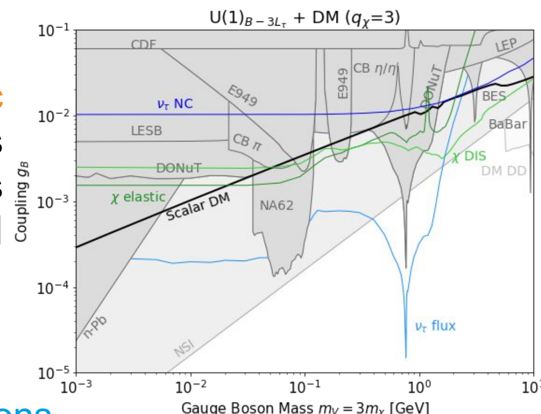
neutrino-philic dark matter production in neutrino interactions $\nu\, q \rightarrow \phi\, l\, q'$
[Kelly, Kling, Tuckler, Zhang, in progress]

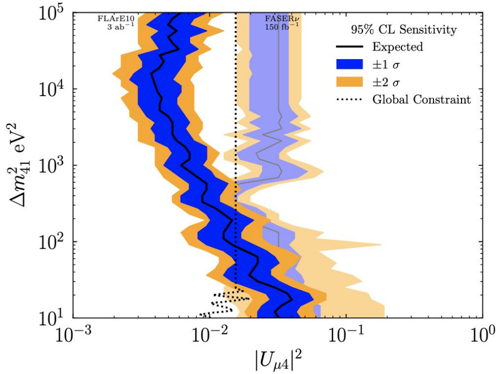




Quirks via nonstandard tracks
[2108.06748]

light tau-neutrino philic mediators: modified fluxes and interactions
[Batell et al, in progress]





Sterile Neutrino Oscillations
[performed by Peter Denton]

Experimental Program:

FASER - FASERν - FPF

Searches for BSM physics:

LLPs - DM - mCPs

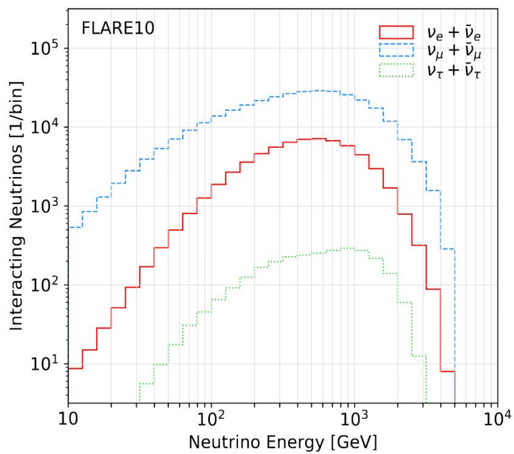
SM Measurements:

Neutrinos - QCD - Cosmic Rays

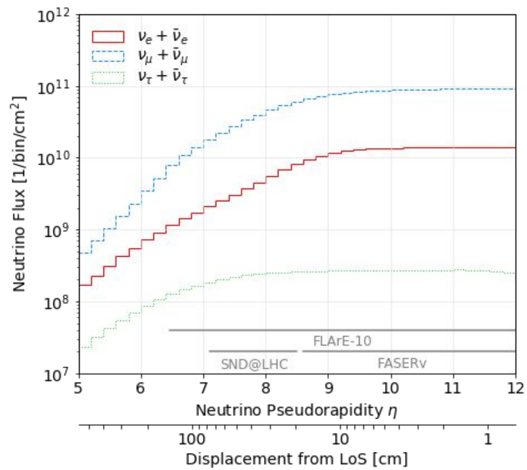
Neutrino Fluxes and Rates.

ATLAS produces an intense, highly energetic and strongly collimated neutrino beam of all three flavours in the far forward direction.

energy spectrum of interacting neutrinos



neutrino flux as function of displacement from LoS



100 GeV - few TeV energies

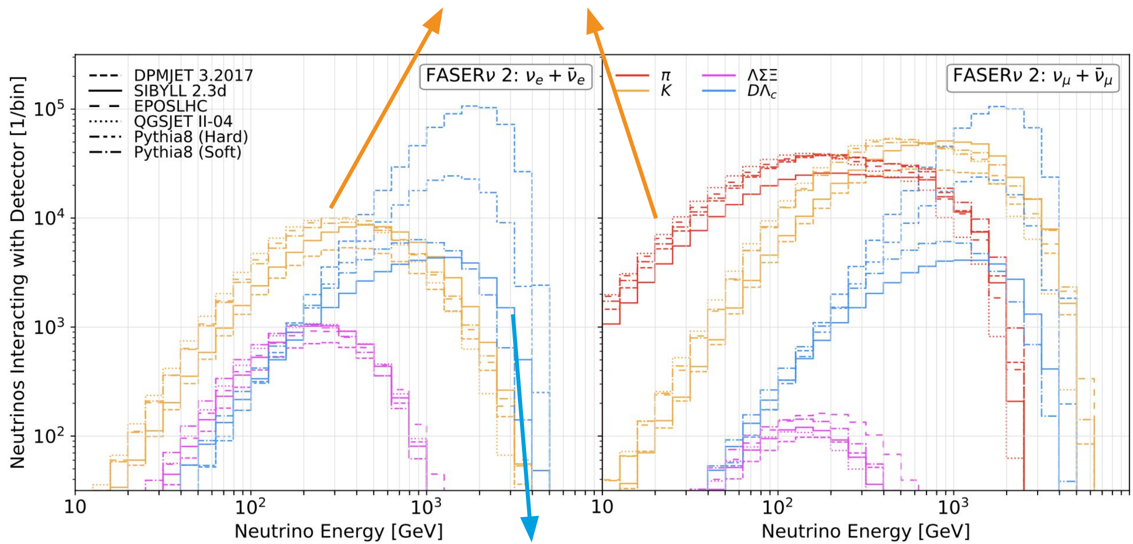
flux peaked around LoS, start to drop around 1m away from LoS

complementary coverage of FASERν and SND@LHC

Neutrino Production.

Forward particle production is poorly constrained by other LHC experiments. The measurement of neutrinos fluxes at the FPF will provide novel complimentary constraints on forward particle production.

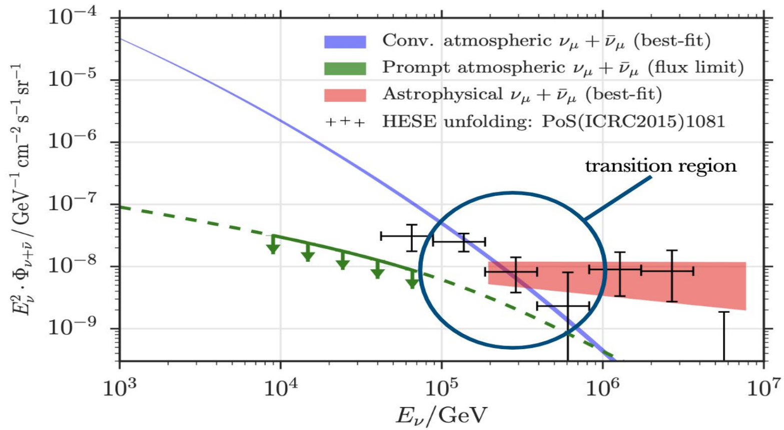
pions & kaons: improve MC generators, cosmic ray muon puzzle

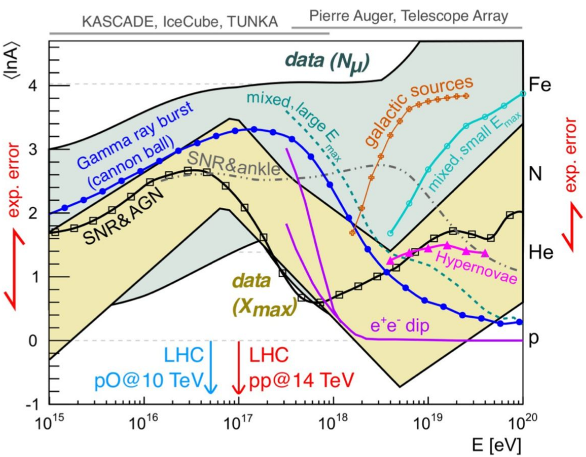


charm: perturbative QCD, test transition to small-x factorization, constrain low-x gluon PDF, probe gluon saturation, probe intrinsic charm, constrain prompt atmospheric neutrino flux at IceCube.

Neutrino Production.

Measuring forward charm production at the LHC would help to constrain the (currently very poorly constrained) prompt atmospheric neutrino flux at IceCube.





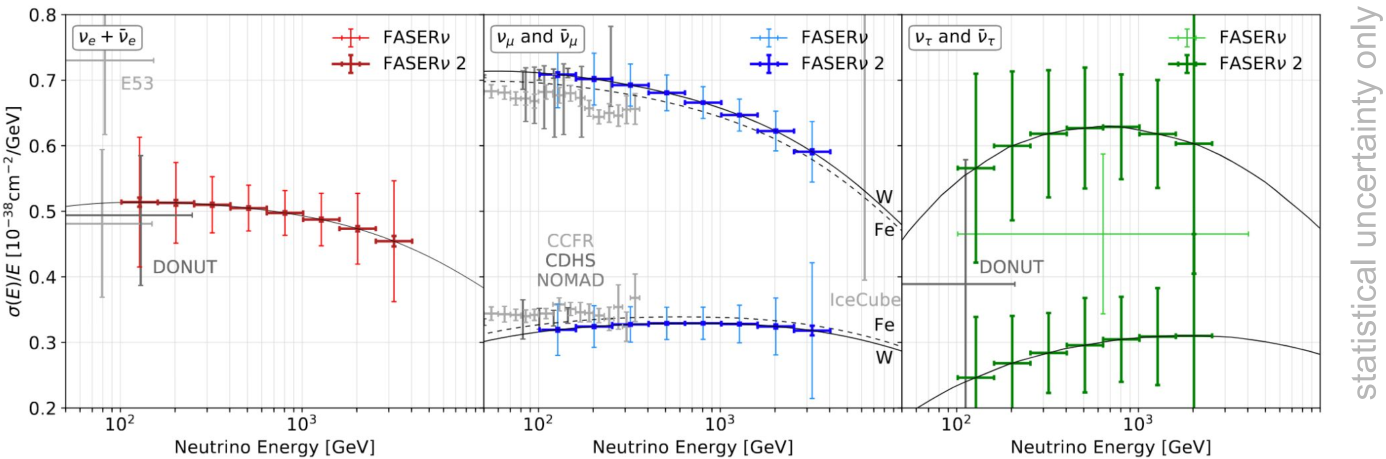
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Cosmic Ray experiments have reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data at the few σ level (muon problem in CR physics).

Measurements of forward hadron production (kaons) at the LHC are crucial to solve this issue.

Neutrino Interactions.

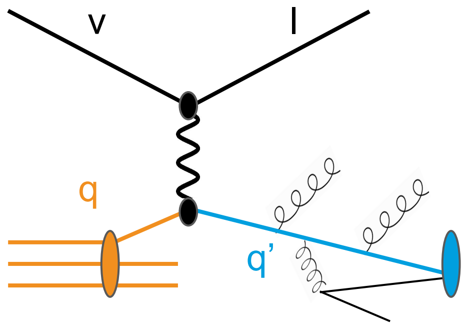
Using LHC neutrinos, one can measure neutrino cross section at unexplored TeV energies for all three flavors. Both CC and NC are possible.



FASERv will detect ~10 tau neutrino interactions, which is similar to DONuT and OPERA. Thousands of tau neutrino events possible at HL-LHC, allowing for precision studies of tau neutrino properties.

Neutrino Interactions.

The FPF is essentially a Neutrino-Ion collider with sqrt(s)~50GeV



Final State

response of cold nuclear matter to fast moving quarks

medium-induced energy losses

fragmentation functions

final state interactions

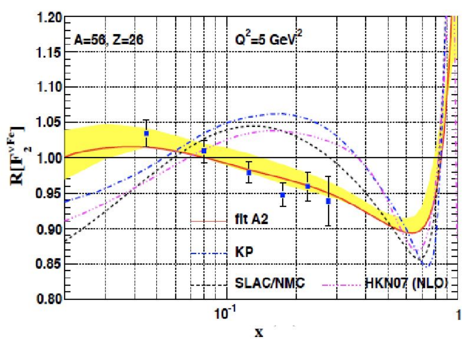
color transparency

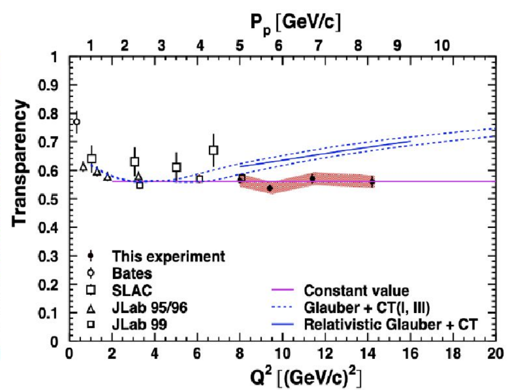
Initial State

nuclear PDFs via measurements on different targets

strange quark PDFs via v s → l c

EMC effect for neutrinos





Summary.

With FASER and SND@LHC, the first experiments will soon start to perform searches for new particles and neutrino measurements in the far-forward region of the LHC.

We propose to continue this program with improved detectors as part of a Forward Physics Facility at the HL-LHC. This will open up many many new opportunities for BSM physics searches, neutrino physics and QCD, significantly extending the LHC's physics program.

↓

We would like to invite the HEP community to help us explore and better understand the physics potential of this program.
You are welcome to join!

For questions and comments, please contact me via felix.kling@desy.de

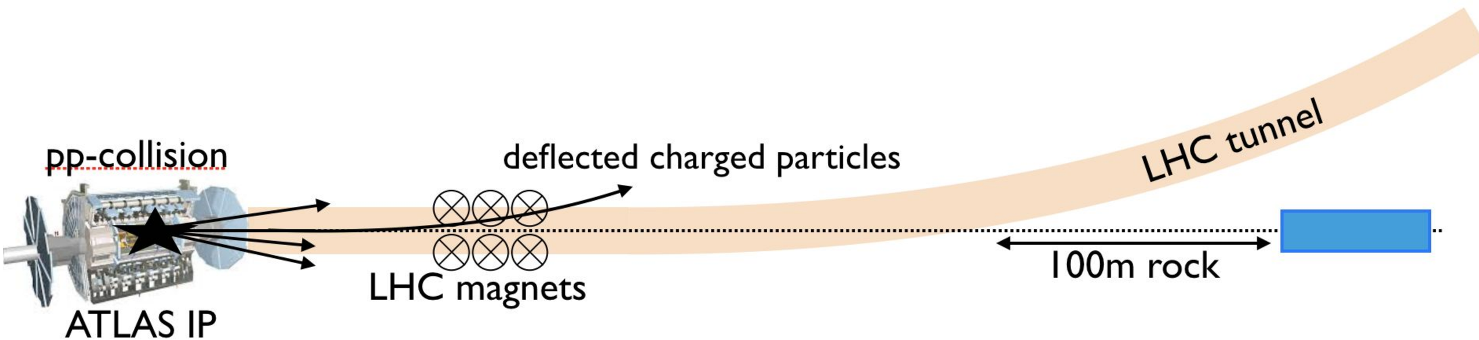
Backup.

Location.

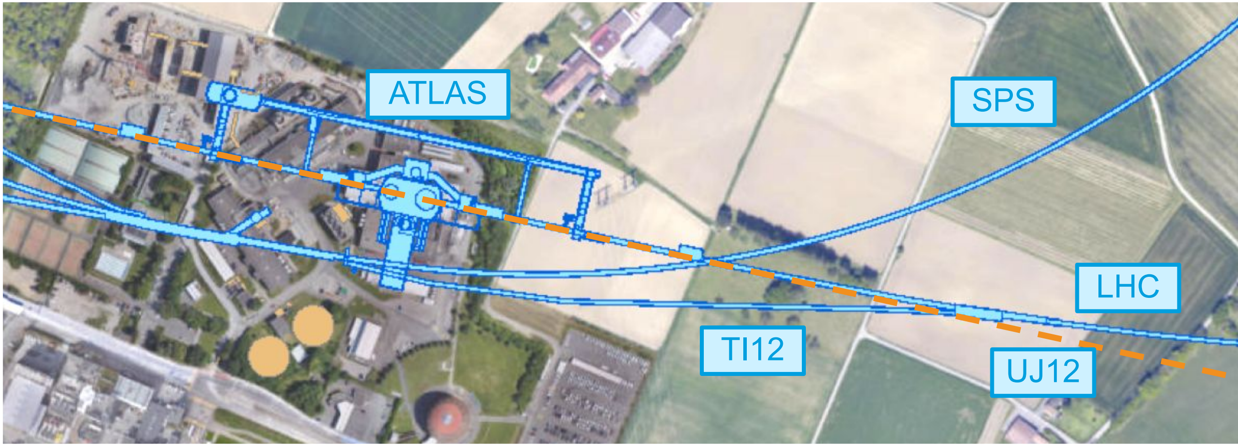
We can't place a reasonably-sized detector on the beam line near the IP
 * blocks the proton beams, subject to large radiation

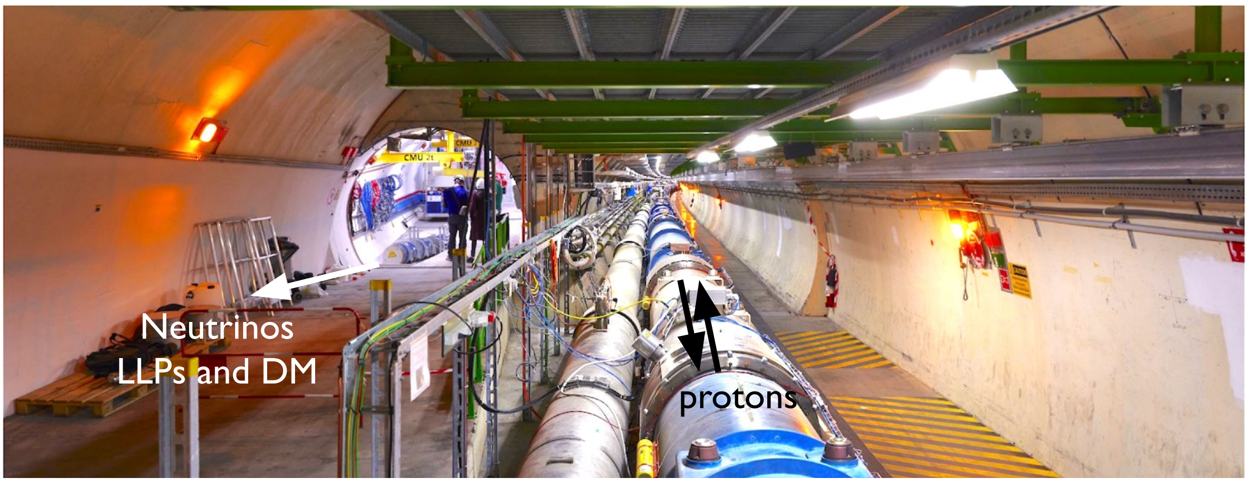
However, weakly-interacting particles do not interact with matter
 * place detector few 100m away along the "collision axis" after beam curves
 * LHC infrastructure acts and rock act as shielding

At this location, particles are still highly collimated
 * 100m x mrad ~ 10cm spread in transverse plane



Location.





FASER Detector.

Main Goal: Search for light long-lived particles

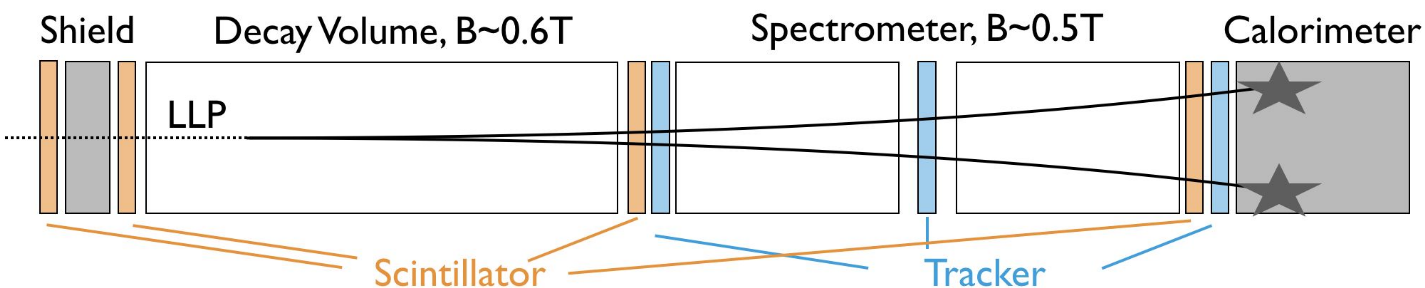
pp → LLP + X,   LLP travels ~ 480m,   LLP → charged tracks + X

Signal is striking:

* two opposite-sign, high energy (E > 500 GeV) charged particles
* originate from a common vertex in a small, empty decay volume
* point back to the IP through 90 m of rock

Background considerations:

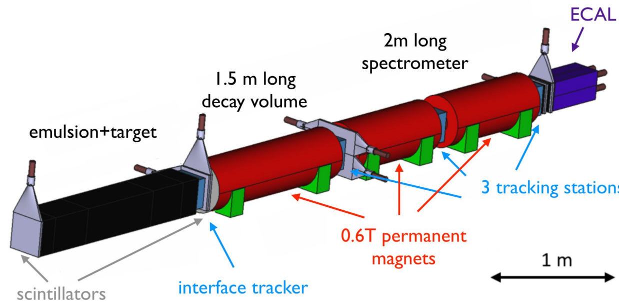
* cosmic rays and neutrino interactions (different kinematics) not a problem
* HE muon-associated radiative events are leading BG if muon is not vetoed
* incoming muons can be identified using scintillators
  → reduce BG to negligible levels



FASERν.

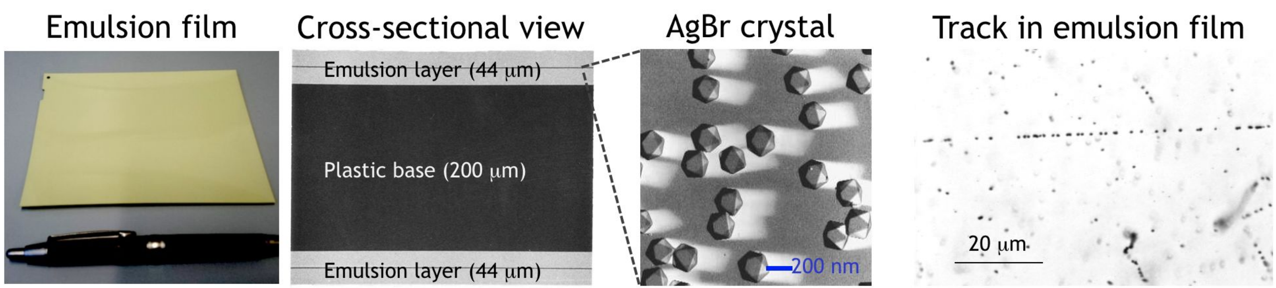
FASERν neutrino detector in front of FASER

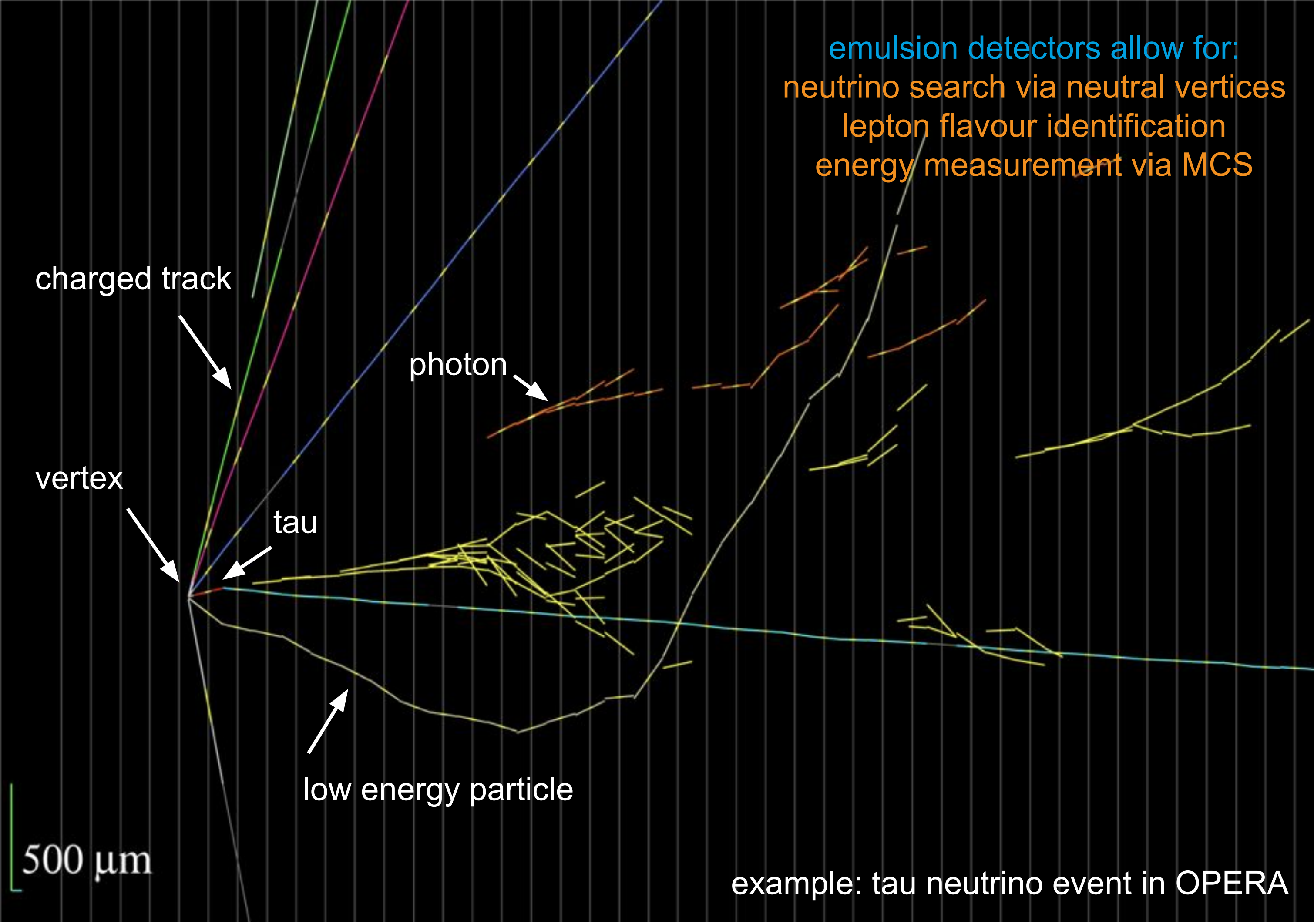
* 25cm x 25cm x 1.3m emulsion detector
* tungsten target with 1.2 ton mass
* placed on-axis: η > 9 angular coverage
* ~1000 νe, ~10000 νμ, ~10 ντ
  during LHC Run 3



Emulsion detectors technology

* used by many other neutrino experiments: CHORUS, DONUT, OPERA
* 1000 emulsion films interleaved with 1mm tungsten plates
* 3D tracking devices with 50 nm spatial precision
* global reconstruction with the FASER detector possible



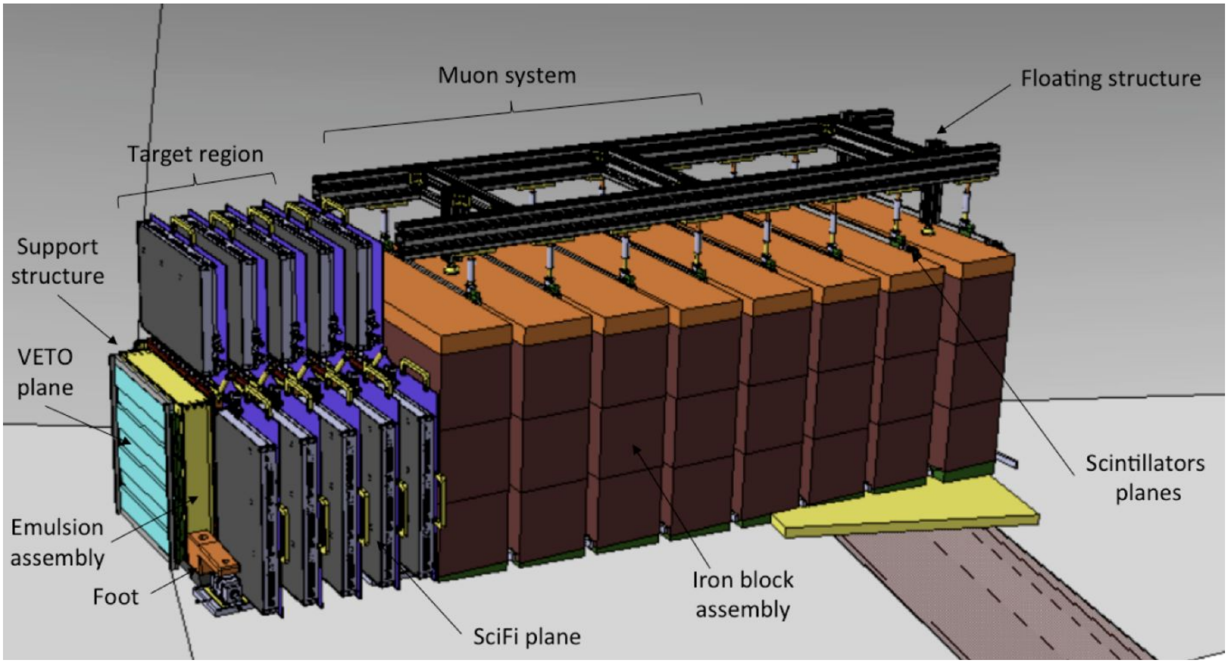

emulsion detectors allow for:
neutrino search via neutral vertices
lepton flavour identification
energy measurement via MCS
charged track
photon
vertex
tau
low energy particle
500 μm
example: tau neutrino event in OPERA

SND@LHC.

contains both emulsion and electronic components

off-axis location: $7.2 < \eta < 8.7$ angular coverage

target: 830 kg of tungsten



Neutrino Fluxes and Rates.

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

	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754

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 Fluxes and Rates.

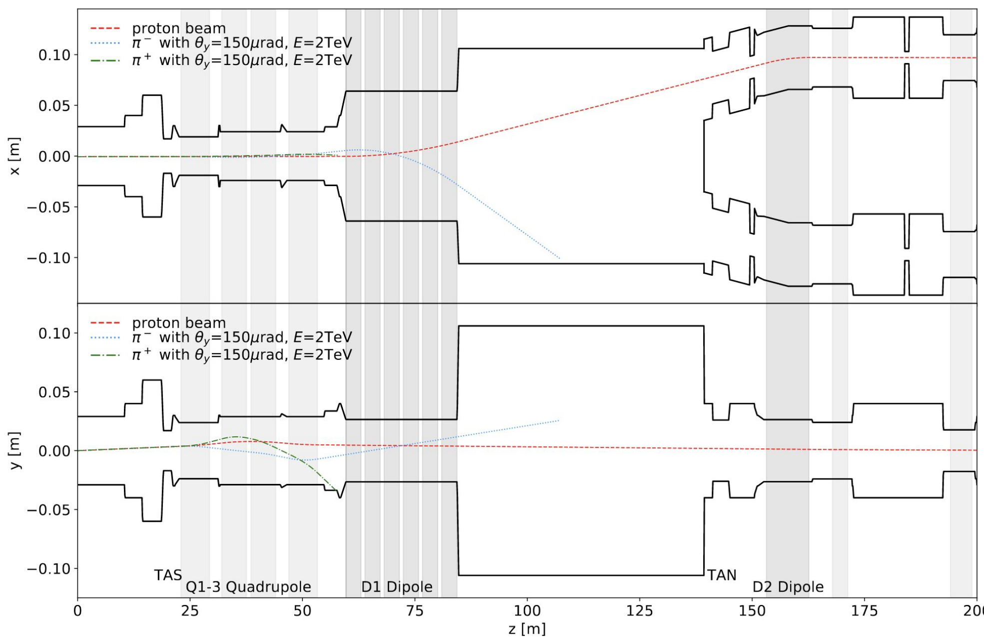
The large majority of neutrino produced close to primary collisions inside the vacuum beam pipe. For those, one needs to model the propagation of hadrons through the LHC as well as their decays.

This has been realized as fast neutrino flux simulation implemented as RIVET module.

[Kling, 2105.08270]

Procedure:

1) simulate collision with MC generator
2) propagate long-lived hadrons through LHC beam pipe and magnets
3) decay hadrons along their trajectory
4) fill neutrinos in histograms

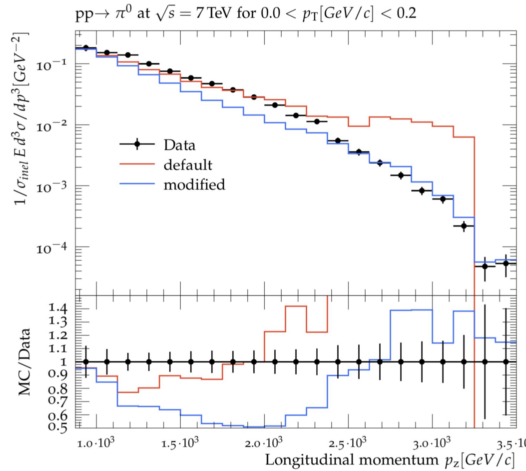


Neutrino Production.

Light hadron production is not described by pQCD

Use hadronic interaction models, often originating from CR physics.

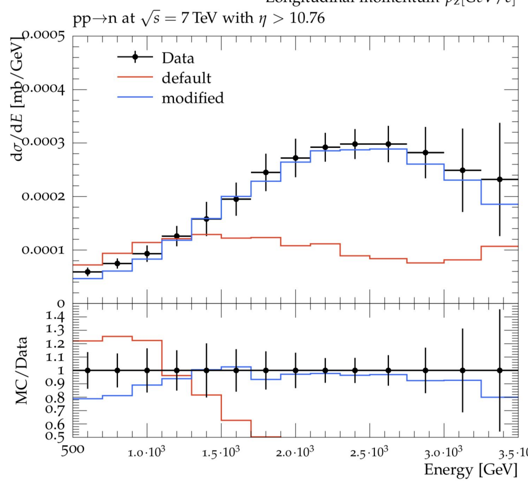
Sophisticated description of microscopic physics with many phenomenological parameters tuned to data.



Currently: Use spread of generators as measure for uncertainty.

Proposal: create a dedicated forward physics tune in Pythia8 using LHCf measurements including tuning uncertainties (similar to PDF uncertainties)

[Fieg, Kling, Schulz, Sjorstrand, in progress]



Neutrino Production.

Neutrinos from charm decay could allow to test transition to small-x factorization, constrain low-x gluon PDF, probe gluon saturation, and probe intrinsic charm.