Neutrinos at CERN

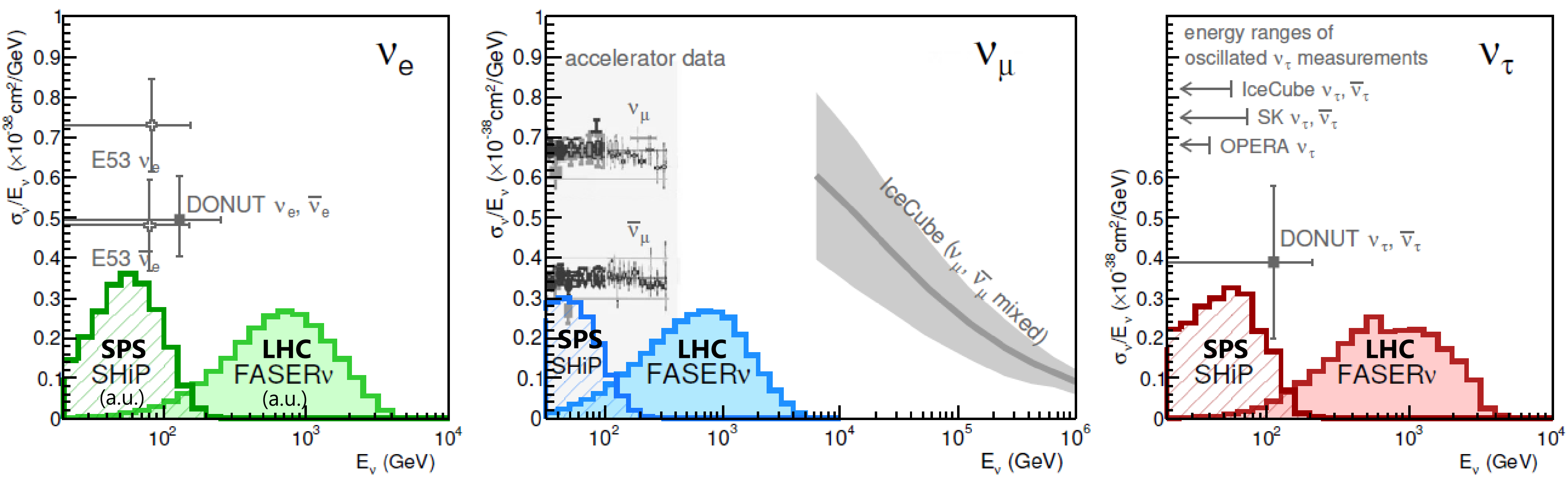
Tomoko Ariga (Kyushu University)

This talk has been prepared with the FASER, NA65/DsTau, SHiP, SND@LHC, XSEN Collaborations

Other neutrino-related activities in Neutrino Platform, NA61, NA62, ENUBET are covered by the other talks

Physics motivations

- Studying high-energy neutrinos in unexplored energy regime
  - Use neutrinos from the **LHC**
  - High energy frontier of man-made neutrinos
  - Cross section measurements of different flavors at high energy
    - ν_τ and ν_e at the highest energy ever
  - Search for new physics effects
- Studying tau neutrinos
  - One of the least studied particles
  - Only a few measurements
    - Direct ν_τ beam: DONuT
    - Oscillated: OPERA, Super-K, IceCube
  - Large uncertainty on the cross section
  - Precise study with high-statistics experiments at the **SPS**



Neutrino experiments discussed in this talk

- New experiment/projects at the LHC to study high-energy neutrinos in unexplored energy regime
  - **FASERν**: Technical proposal in Oct. 2019. **Approved by CERN in Dec 2019**. Preparing for data taking in LHC Run3 (2021-2024).
  - **XSEN, SND@LHC**:
  - XSEN **Letter of Intent in Sep 2019**.
  - SND@LHC **Letter of Intent in Feb 2020**. Aiming to take data from 2022.

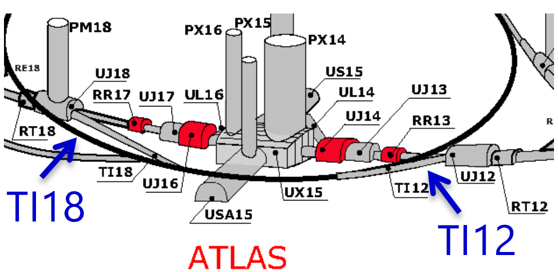
- Fixed-target experiments at the SPS for high-statistics tau-neutrino studies
  - **SHiP neutrino program** for detecting ν_τ with high statistics: Technical proposal in Apr 2015 and **Comprehensive Design Report in Dec 2019**. Aiming to take data after LS3.
  - **NA65/DsTau** for studying ν_τ production and forward charm production: **Approved by CERN in Jun 2019**. Physics run from 2021.

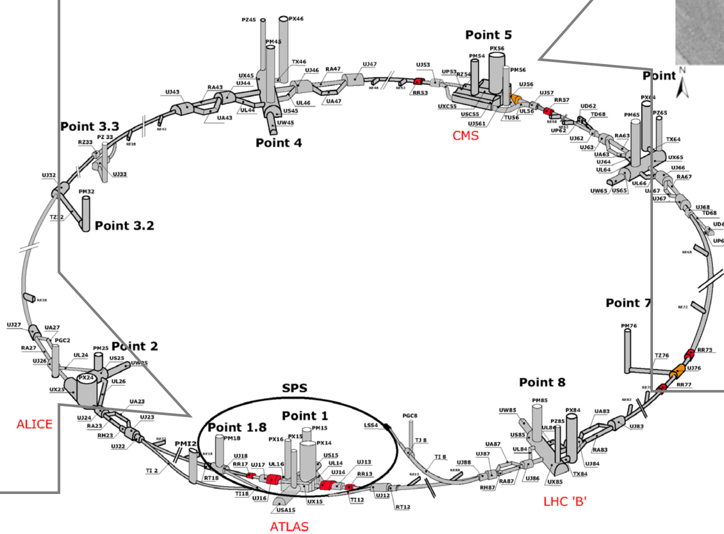
Neutrino experiments at the LHC

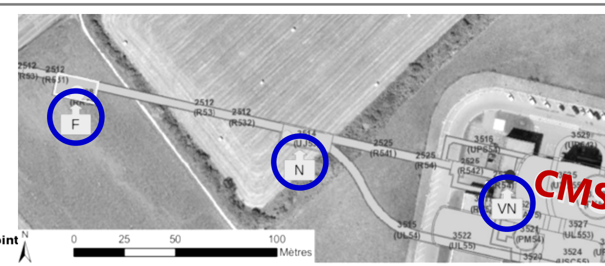
- Exploit the LHC as a neutrino source
- There has been a longstanding interest in detecting them, e.g.,
  - A. De Rujula, R. Ruckl, Neutrino and muon physics in the collider mode of future accelerators (1984)
  - Klaus Winter, Detection of the tau neutrino at the LHC (1990)
  - F. Vannucci, Neutrino physics at LHC/SSC (1993)
  - A. De Rujula, E. Fernandez, J.J. Gomez-Cadenas, Neutrino fluxes at future hadron colliders (1993)
  - H. Park, The estimation of neutrino fluxes produced by proton-proton collisions at √s = 14 TeV of the LHC (2011)
- Investigation of possible sites has been performed in recent years

Possible sites

FASER/FASERν investigated the background in the tunnels **TI18 and TI12**, 480 m from the ATLAS IP.







XSEN investigated the background around CMS

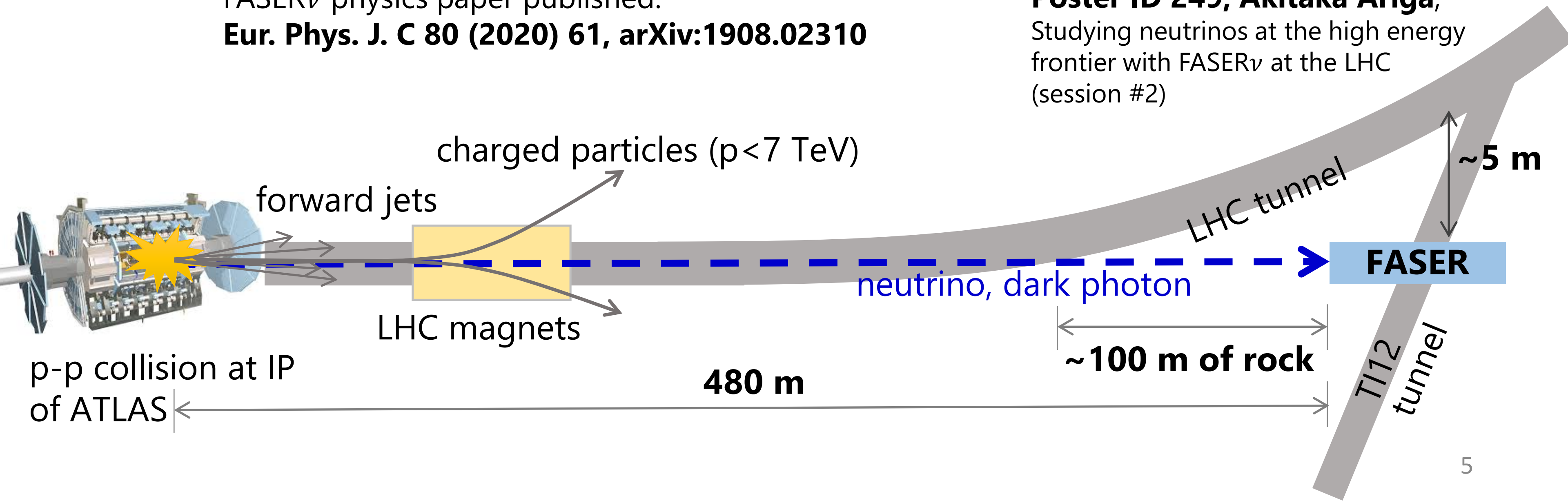
- VN: Q1 at 25 m
- N: UJ53, UJ57 at 90, 120 m
- F: RR53 at 240 m

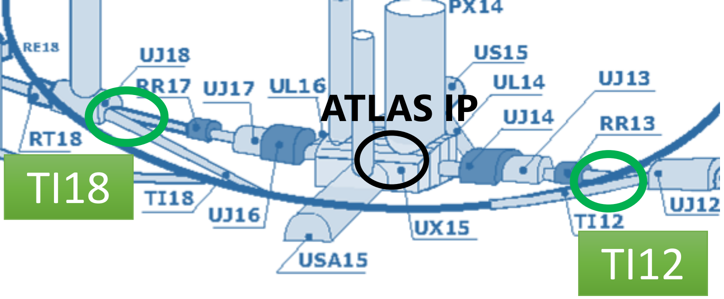
FASERν

- FASER is a small and fast experiment to be installed in the LHC to take data in LHC Run3.
- **FASER (new particle searches) approved by CERN in Mar. 2019.**
  - Targeting light, weakly-coupled new particles at low p_T .
  - Funded by the Heising-Simons and Simons Foundations with support from CERN.
- **FASERν (neutrino measurements) approved by CERN in Dec. 2019.**
  - Will perform first measurements of neutrinos from a collider and in unexplored energy regime.
  - The detector will be centered on the beam axis to maximizes fluxes of all neutrino flavors.
  - Funded by the Heising-Simons Foundation and grants from JSPS and the Mitsubishi Foundation.

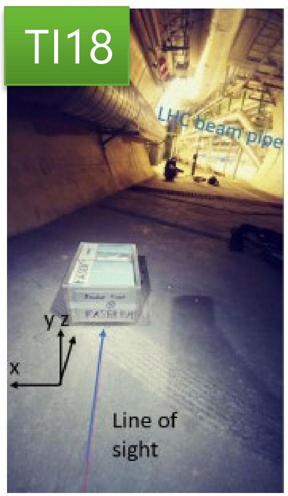
FASERν physics paper published:
Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

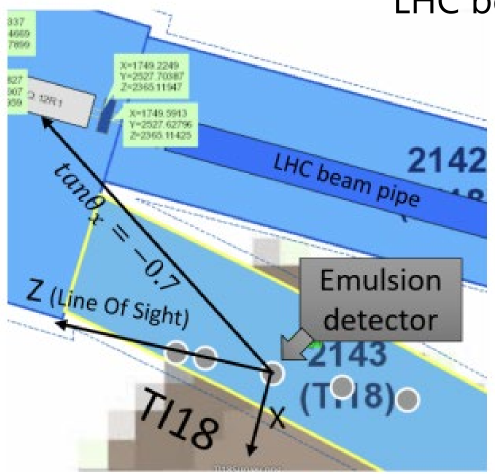
Poster ID 249, Akitaka Ariga,
Studying neutrinos at the high energy frontier with FASERν at the LHC
(session #2)

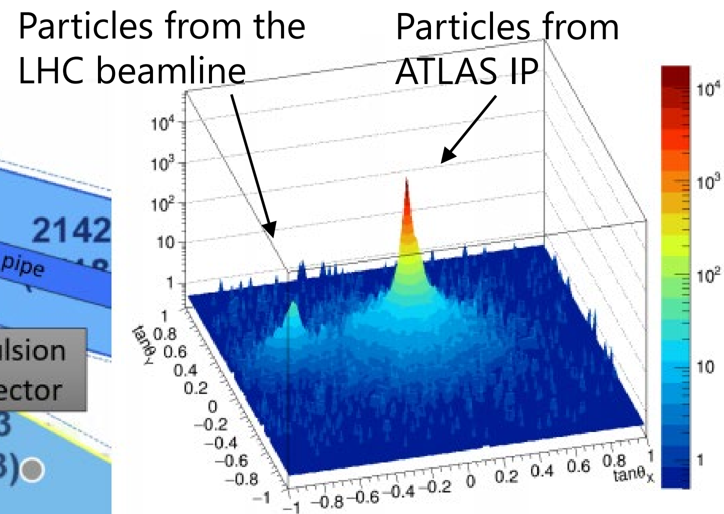


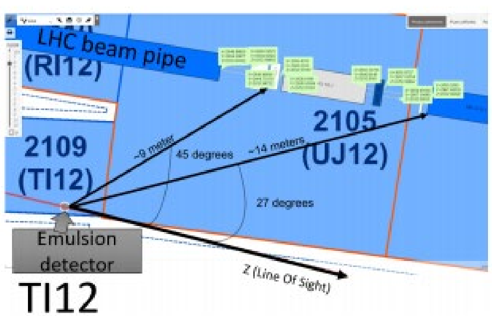


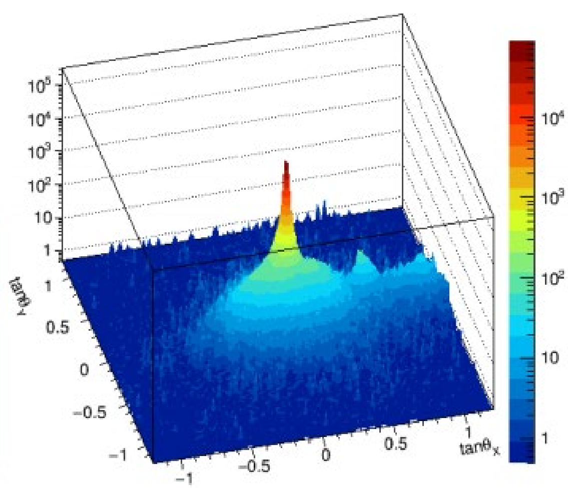
In-situ measurements
in 2018: Detector environment











- Emulsion detectors were installed to investigate TI18 and TI12.
- The measured charged particle flux was low and consistent with the FLUKA prediction.

	Normalized flux (fb/cm^2)
TI18	$(2.6 \pm 0.7) \times 10^4$
TI12	$(3.0 \pm 0.3) \times 10^4$

- The measurements also showed the radiation was low and not problematic.

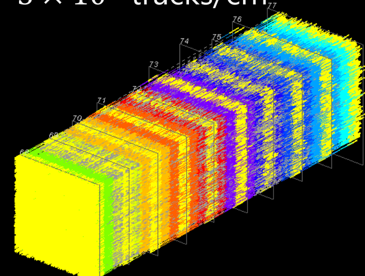
Feasible to perform neutrino measurements!

2018 test run data:

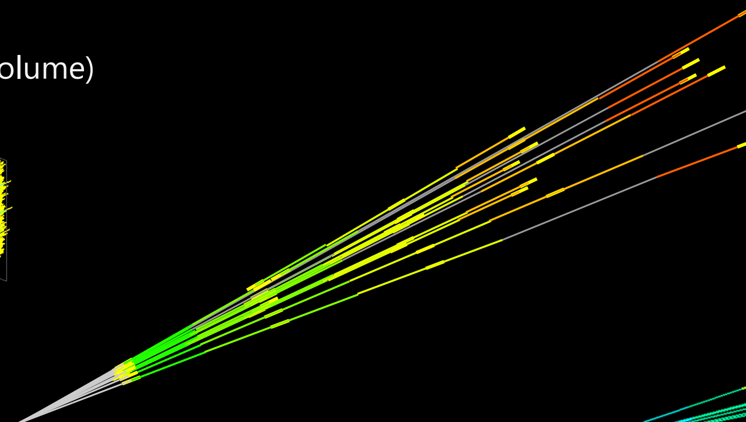
Towards first detection of neutrinos from the LHC

line of sight

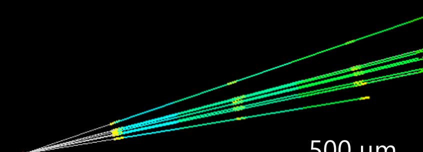
Reconstructed data (sub-volume)
$\simeq 3 \times 10^5$ tracks/cm^2



1000 µm



500 µm



500 µm

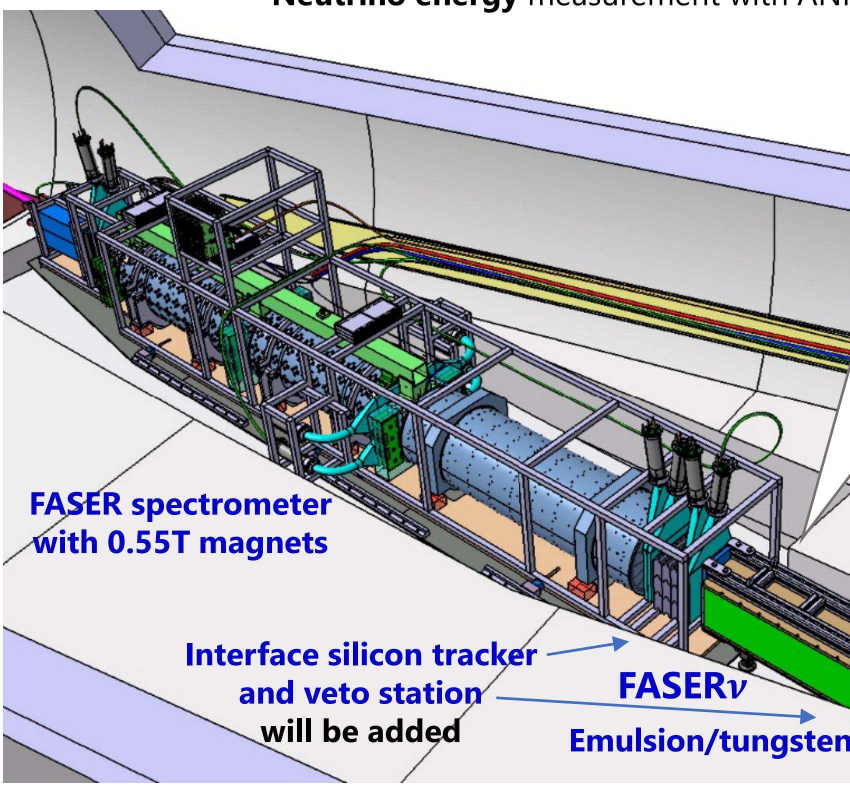
- A 30 kg emulsion detector was installed in TI18 during 2018 running and 12.5 fb^{-1} data collected.
- Emulsion films were developed and scanned.

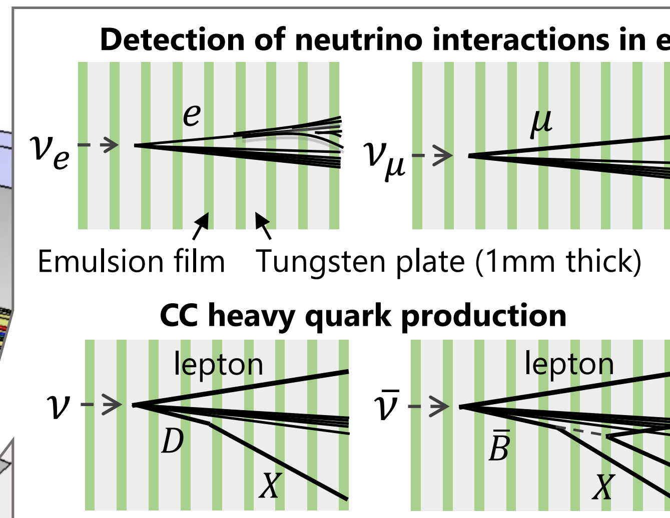
- Detected several neutral vertices (neutrinos or neutral hadrons).
- Working on the robust background estimate.

FASERν detector will have better performance (longer detector with muon ID capability).

Detector for the LHC Run3 (2021-2024)

- **Emulsion/tungsten detector** and interface silicon tracker will be placed in front of the main FASER detector to be coupled with the **FASER magnetic spectrometer**.
- **Allows to distinguish all flavor of neutrino interactions.**
  - 1000 1-mm-thick tungsten plates, interleaved with emulsion films
  - 25x25 cm^2, 1.3 m long, 1.2 ton detector ($285X_0$)
  - Emulsion films will be replaced every 30-50 fb^{-1} during scheduled LHC technical stops (3 times per year)
  - **Muon identification** by their track length in the detector ($10\lambda_{int}$)
  - **Muon charge identification** with hybrid configuration → distinguishing ν_μ and $\bar{\nu}_\mu$
  - **Neutrino energy** measurement with ANN by combining topological and kinematical variables ($\Delta E/E$ ~30%)

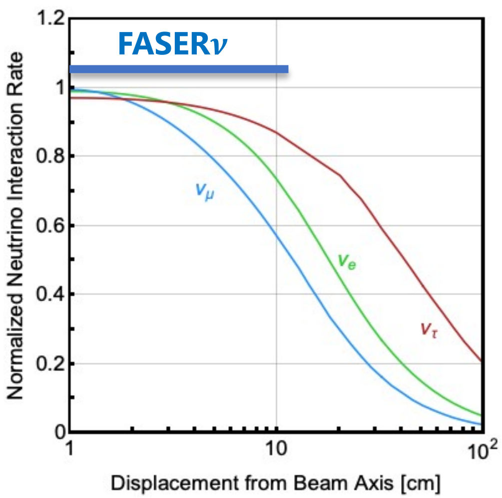




Interface tracker will be made of 3 layers of double sided silicon micro-strip detectors (spare ATLAS SCT modules).
Many thanks to the ATLAS SCT Collaboration.

Neutrino event rate

- **FASERν will be centered on the LOS** (in the FASER trench) to maximizes fluxes of all neutrino flavors.
- **~10000 CC interactions are expected in LHC Run3!**

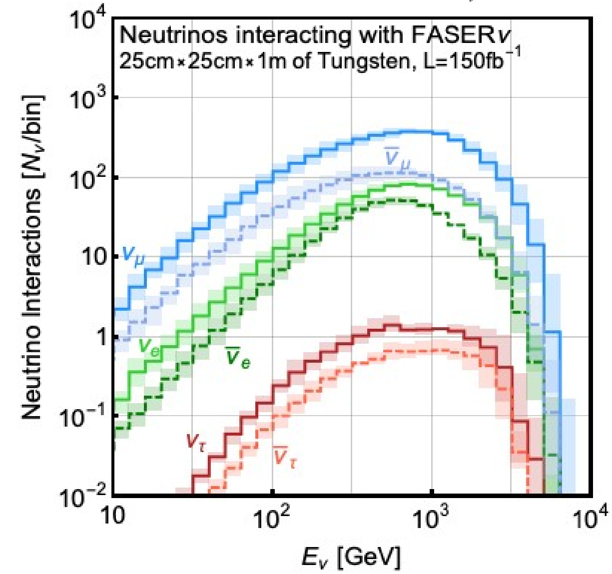


Expected number of CC interactions in FASERν in Run3 (14 TeV LHC, 150 fb^{-1})

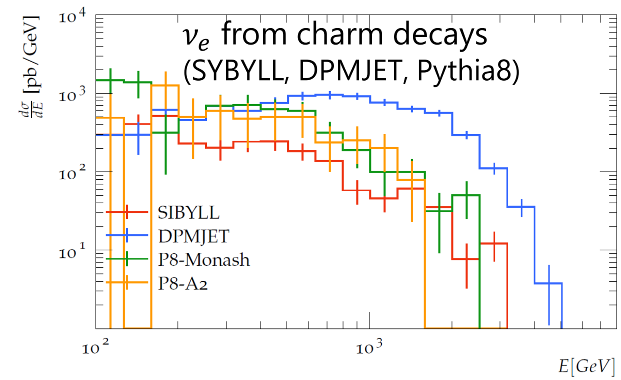
	LOI	FLUKA
ν_e , $\bar{\nu}_e$	814 , 456	2986 , 1261
ν_μ , $\bar{\nu}_\mu$	4452 , 1366	8437 , 2737
ν_τ , $\bar{\nu}_\tau$	15 , 7	110 , 55

For the LOI, EPOS-LHC, QGSJET and SIBYLL (for light hadrons) and SIBYLL and Pythia8 (for heavy hadrons) were used. For the FLUKA simulation, DPMJET was used.

Thanks to F. Cerutti, M. Sabaté-Gilarte, A. Tsinganis, and the CERN STI group for the FLUKA simulation.



Difference of the generators



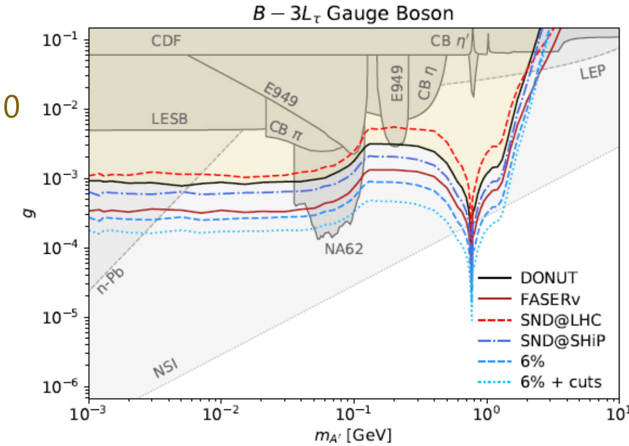
- **The LOI estimates have been cross checked independently.**
  - Differences in the simulations (generators, magnets) were identified. Updating the neutrino fluxes is in progress.
- **Work in progress for quantifying and reducing these uncertainties.**
  - Creating a dedicated forward physics tune with Pythia8, using forward data.
  - Including tuning uncertainties.

Other theoretical study:
Poster ID 118, Neutrinos in the far-forward region at the LHC (session #2)

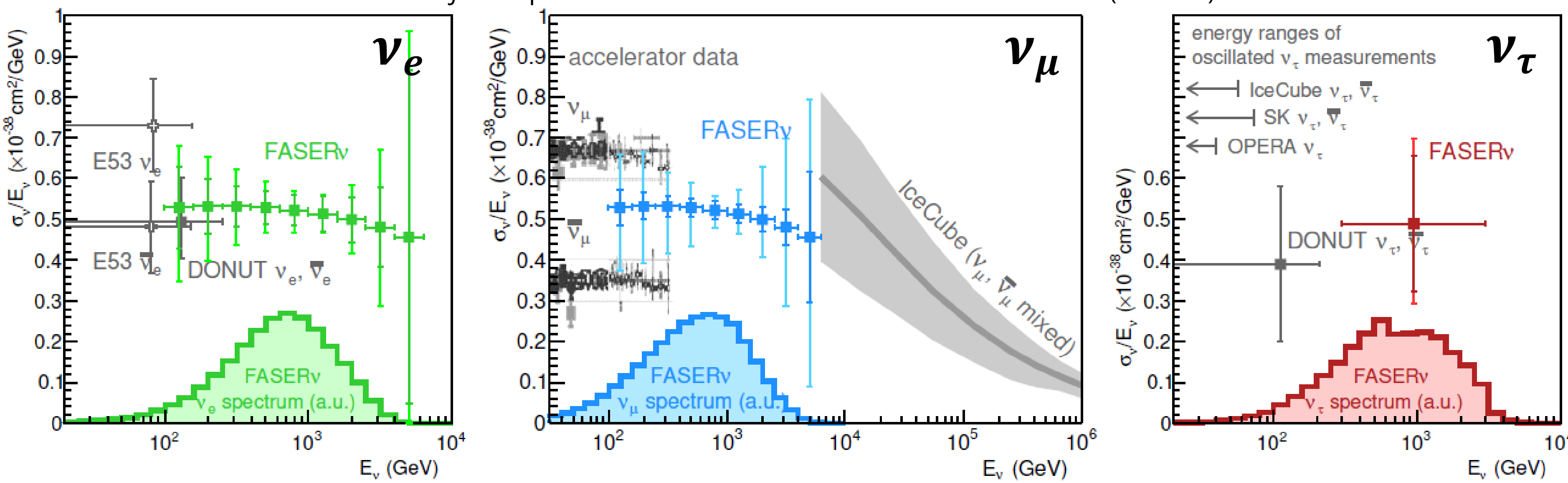
Prospects for 2021-2024

- **Cross section measurements at high energy**
  - Three flavors in an energy range where cross sections are unconstrained
- **Additional physics studies** Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310
  - Charm/beauty production channels in ν CC
  - Neutrino production via heavy meson decays → Intrinsic charm and prompt neutrino study
  - Possibility to study sterile neutrino oscillations
  - Possibility to probe new physics models

Possibility of probing tau neutrino production from the decay of light gauge bosons, F. Kling, arXiv:2005.03594



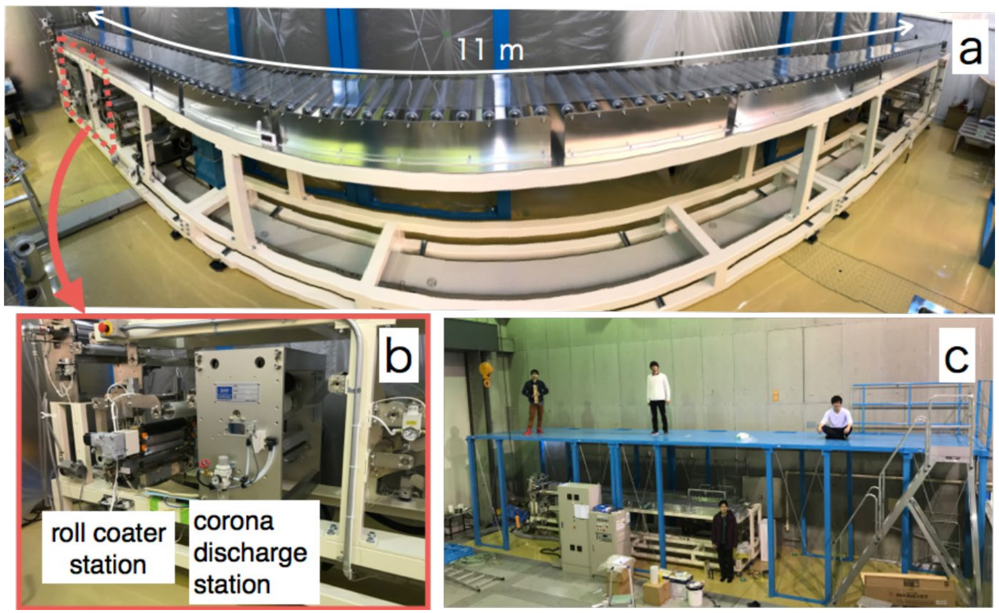
Projected precision of FASERν measurement at 14-TeV LHC (150 fb^{-1})



Emulsion detector technology

Thanks to H. Rokujo, M. Yoshimoto, T. Nakano

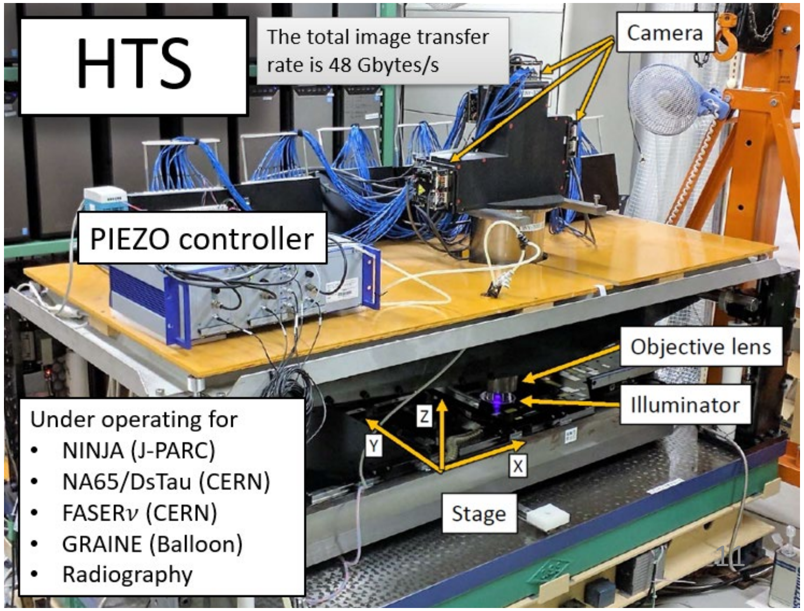
- **Detector production**
  - Upgrading the emulsion facility in Nagoya University
    - Large-scale gel production machine and film production system
  - Targeted performance of the film production system: 12.5 m^2/day
  - Would be ready for mass production in July-August 2020



- **Fast readout of emulsion films**
  - Great progress in the readout speed
  - ~100 times faster than OPERA

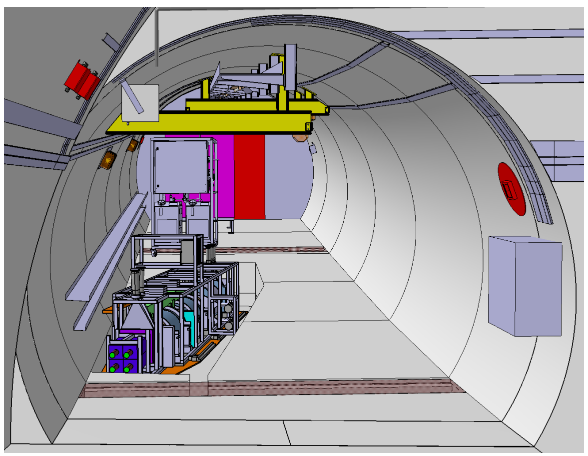
HTS paper: M. Yoshimoto, T. Nakano, R. Komatani, H. Kawahara, PTEP 10 (2017) 103H01.

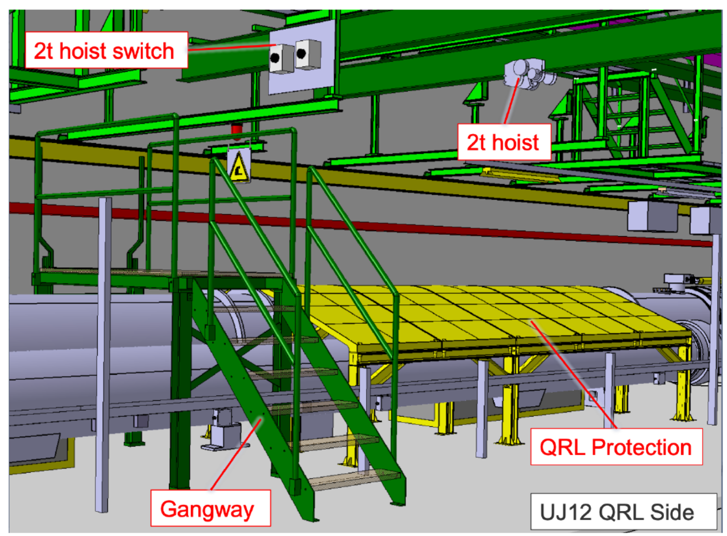
	Start year	Field of view (mm^2)	Readout speed (cm^2/h/layer)
S-UTS	2006	0.05	72
HTS-1	**2015**	**25**	**4700**
HTS-2	2021	50	25000

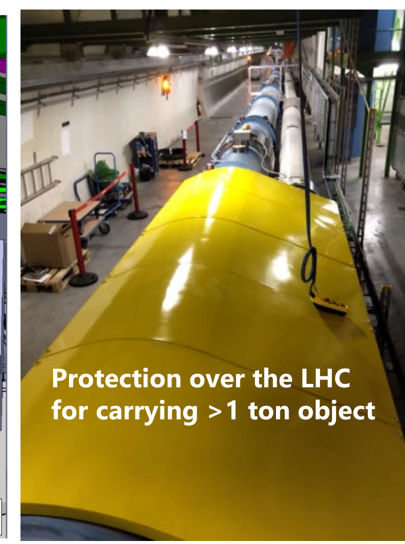


Civil engineering and infrastructure work

- TI12 area was cleaned up.
- **Civil engineering work** to allow FASER/FASERν installation **finished on schedule**, just before the CERN shutdown.
- Access over the LHC machine has been prepared.







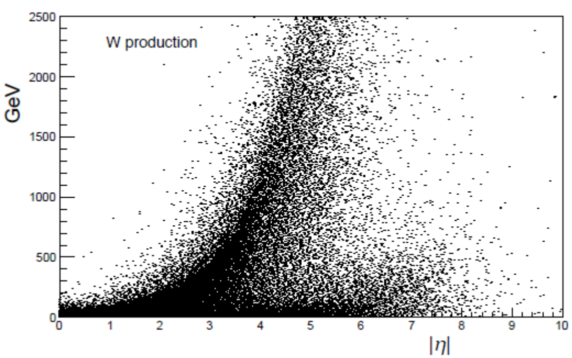
Acknowledge great support from many CERN teams: SMB-FS, EN-ACE, EN-EA, EN-EL, EN-HE, EN-CV, HSE – with support from PBC

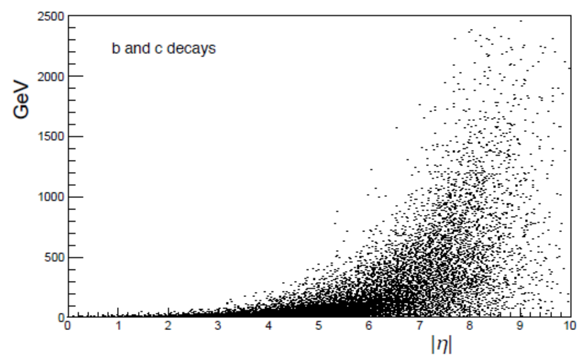
XSEN, SND@LHC proposals

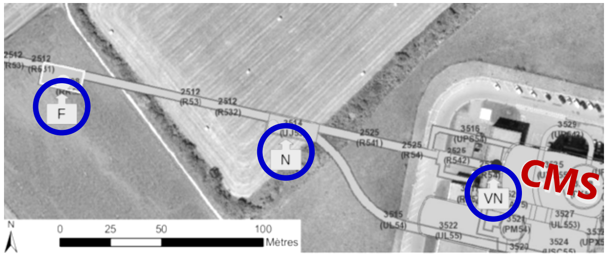
XSEN
SND@LHC

Thanks to G.M. Dallavalle, G. De Lellis

- **XSEN** (X-Section of Energetic Neutrinos) investigated potential and feasibility of a neutrino experiment at the LHC focusing on high energy neutrinos in two η ranges: $4 < \eta < 5$ (leptonic W decays) and $6.5 < \eta < 9.5$ (c and b decays, mostly from D_s decays).
  - S. Buontempo et al., arXiv:1804.04413
  - N. Beni et al., J. Phys. G: Nucl. Part. Phys. 46 (2019) 115008
  - N. Beni et al., arXiv:2004.07828

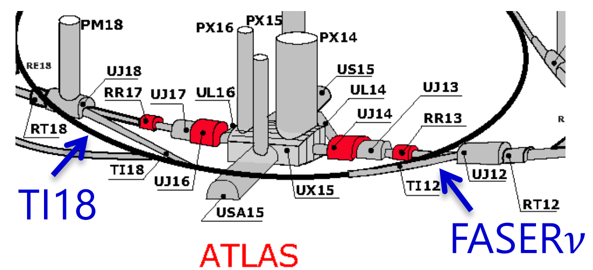






In the 3 sites tested near CMS, prohibitive levels of backgrounds were found.

- Proposed an experiment in TI18
  - The opposite site of FASERν with respect to the ATLAS IP
  - **XSEN** LOI in Sep. 2019 (CERN-LHCC-2019-014 / LHCC-I-033)
  - **SND@LHC** LOI in Feb. 2020 (CERN-LHCC-2020-002 / LHCC-I-035)
    - Aiming to operate off axis (~30 cm from the LOS) to probe a different pseudorapidity range from FASERν.



SND@LHC detector concept

Emulsion Cloud Chamber (ECC), emulsion and Pb absorbers for micrometric production and decay vertex detection of τ and LDM, EM shower energy measurement.

- Number of walls: 4
- Passive material: Lead
- Number of ECC bricks/wall: 12
- Total number of bricks: 48
- Total mass: ~380 kg
- Total emulsion surface: ~35 m²

SciFi with timing, records TOF information of events only present in the target tracker region, track and shower matching between ECCs and add time to the ECC data. EM shower measurement as sampling calorimeter every $10X_0$.

SciFi tracker with 250 μm readout pitch
Timing information with STiC3 ASIC, σ_{CRT}=350 ps
Hit detection efficiency >99%

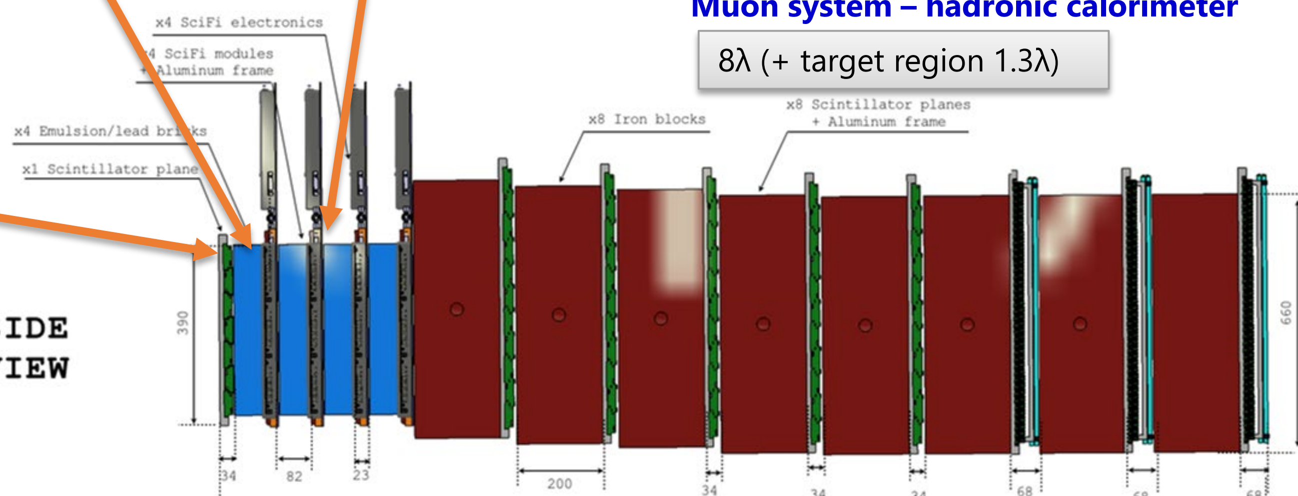
Muon system – hadronic calorimeter

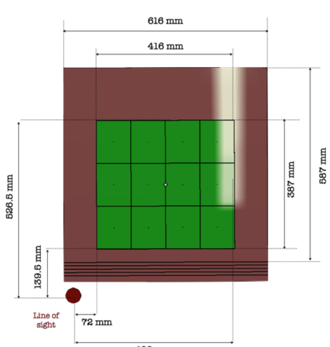
8λ (+ target region 1.3λ)

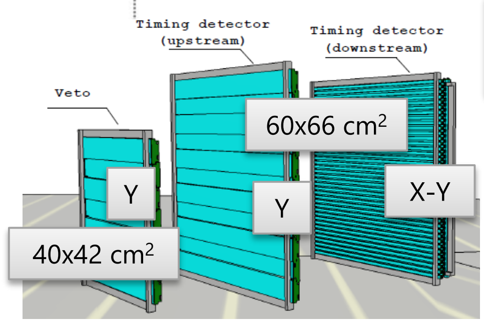
Veto plane for charged particles

ν

SIDE VIEW







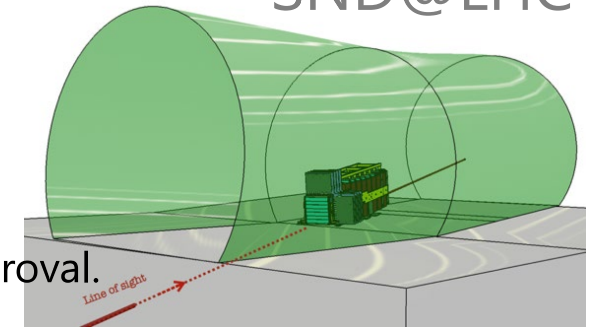
Timing upstream for muon filtering

All horizontal layers with a double sided SiPM readout

Timing downstream, double X-Y planes with higher granularity for muon-hadron separation

Prospects

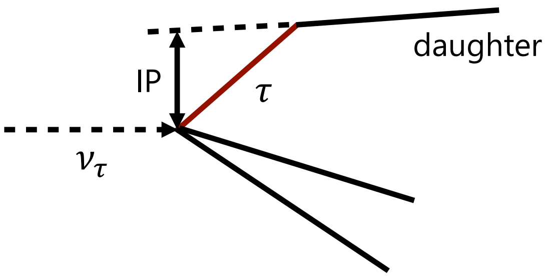
- SND@LHC LOI is to be evaluated in the LHCC.
- The infrastructure can be installed in 6 months from the approval.
- Aiming to start the first run in 2022.



Off-axis (~30 cm from the LOS)

Selection of τ lepton candidates

IP of the daughter track w.r.t. the neutrino vertex >10 μm



Expected event rate by FLUKA with DPMJET

For 25 fb^{-1} (total mass 380 kg)

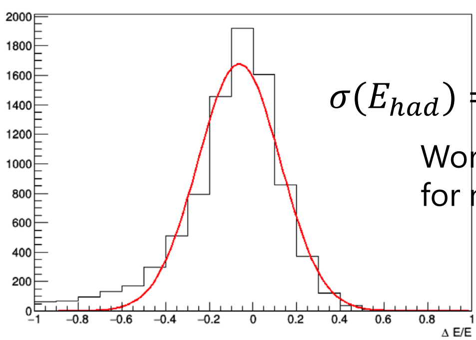
	CC interactions
ν_e , $\bar{\nu}_e$	21 , 11
ν_μ , $\bar{\nu}_\mu$	62 , 27
ν_τ , $\bar{\nu}_\tau$	1 , 0

For 150 fb^{-1} (total mass 850 kg)

	CC interactions
ν_e , $\bar{\nu}_e$	332 , 174
ν_μ , $\bar{\nu}_\mu$	975 , 429
ν_τ , $\bar{\nu}_\tau$	18 , 7

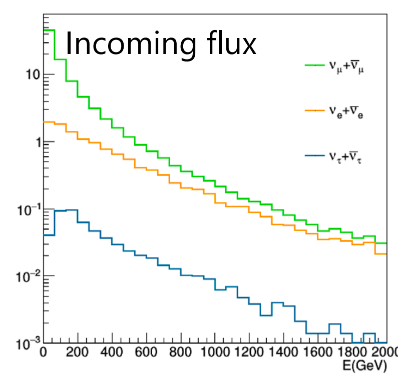
Thanks to F. Cerruti's group for the FLUKA simulation.

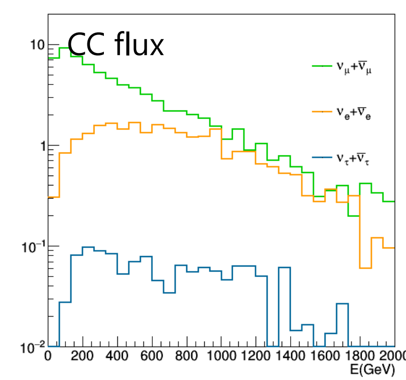
Hadron energy reconstruction



$\sigma(E_{had}) = (18.8 \pm 0.2)\%$

Work in progress for neutrino energy





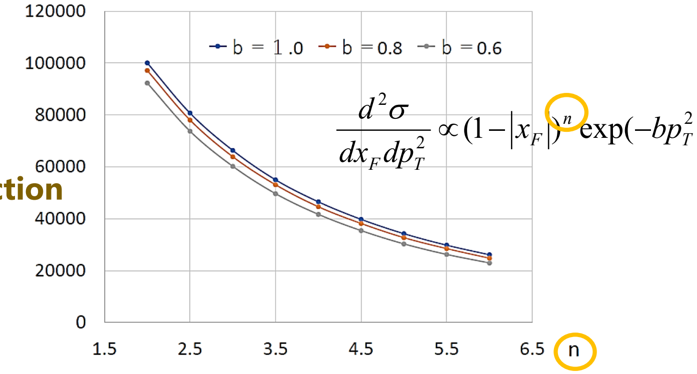
Neutrinos at the SPS

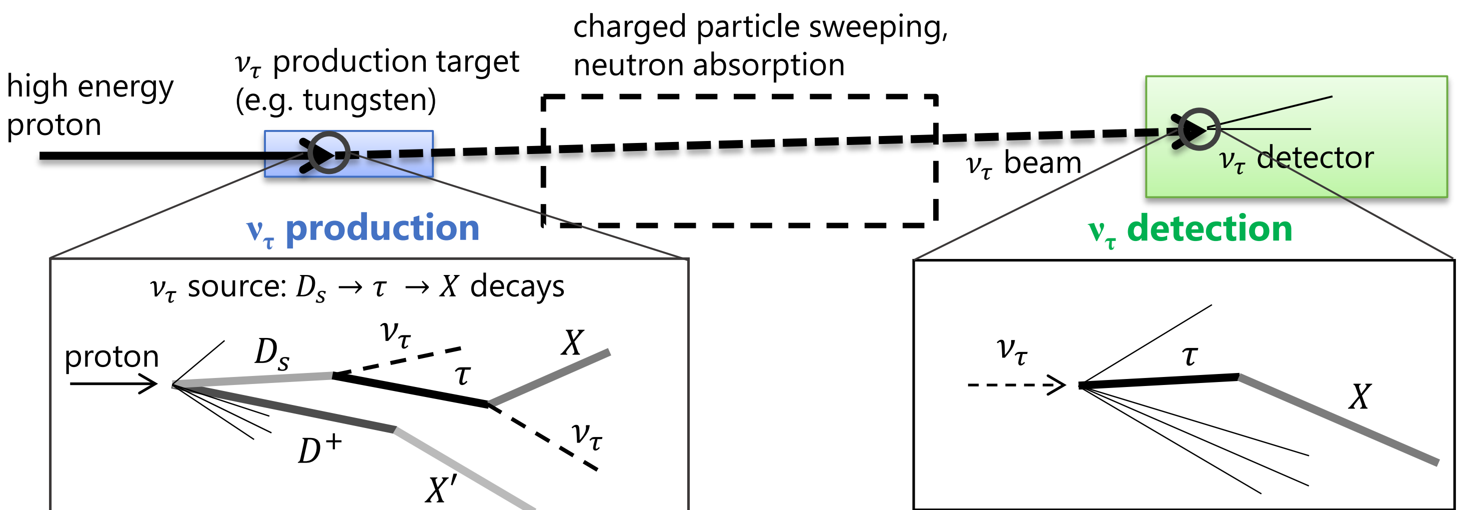
Tau-neutrino studies at the SPS

- **Tau-neutrino measurements with high statistics**
  - Need to study both the production and detection for a precise measurement of the ν_τ cross section

Tau-neutrino event rate strongly depends on the longitudinal dependence of the D_s production

Number of ν_τ interactions in the SHiP neutrino detector





Statistical uncertainty 33% in DONUT. Will be reduced to few % level in future experiments.

No data for D_s differential cross sections for 400 GeV p beam.
Large systematic uncertainty in the ν_τ flux prediction (~50%).

NA65/DsTau, SHiP-charm

SHiP SND@BDF
(SPSC-P-350)

NA65/DsTau experiment

Approved by CERN in June 2019

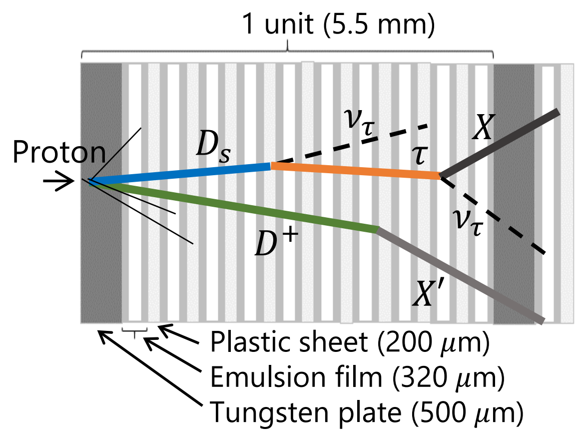
Test beam in 2016-2017
→ Pilot run in 2018
→ Approved as NA65
→ Physics run in 2021-2022

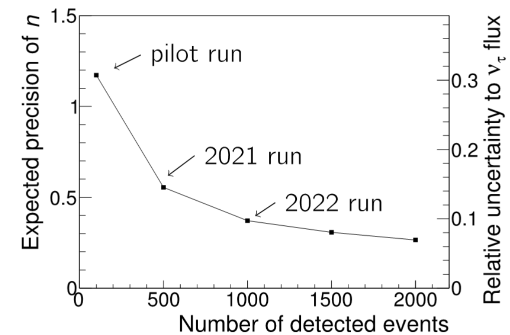
DsTau Collaboration, JHEP 01 (2020) 033. doi:10.1007/JHEP01(2020)033

Poster ID 349, Sergey Dmitrievsky, DsTau (NA65) experiment (session #3)

Physics goals

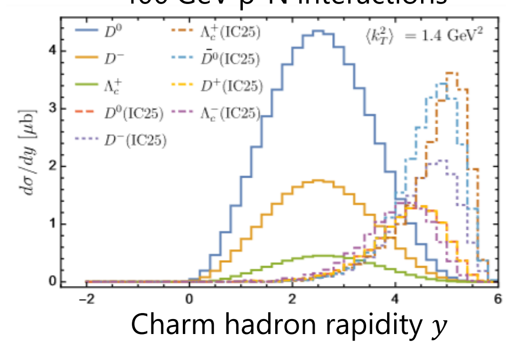
- Measurement of ν_τ production
  - Measurement of D_s differential production cross section
  - Reduction of systematic uncertainty in the cross section measurement
  - **Important input for future ν_τ experiment**: e.g. SHiP neutrino program



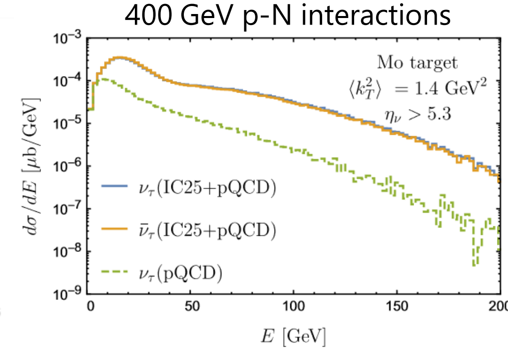


- Forward charm production
  - Source of prompt neutrinos
  - Large experimental and theoretical uncertainties
  - Could be a key input for high-energy neutrino measurements

Charm production in 400 GeV p-N interactions

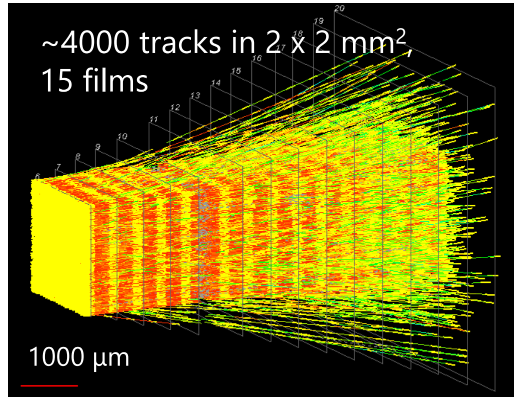


Tau neutrinos from 400 GeV p-N interactions

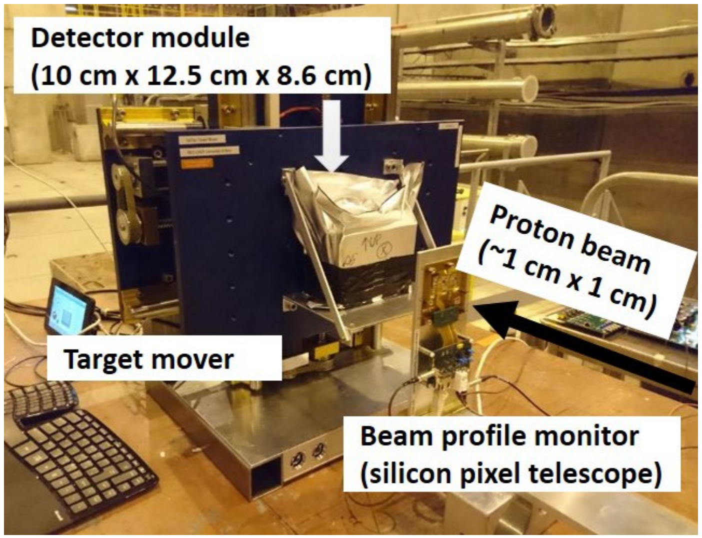


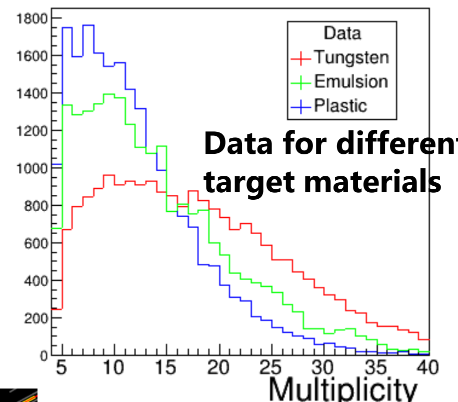
W. Bai, M.H. Reno, JHEP 2019, 77 (2019)

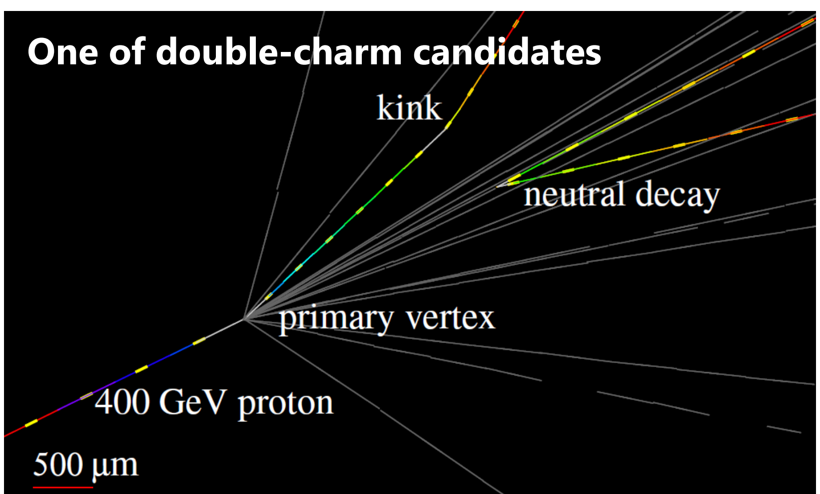
Pilot run data and prospects



Setup at the CERN SPS H4 beamline







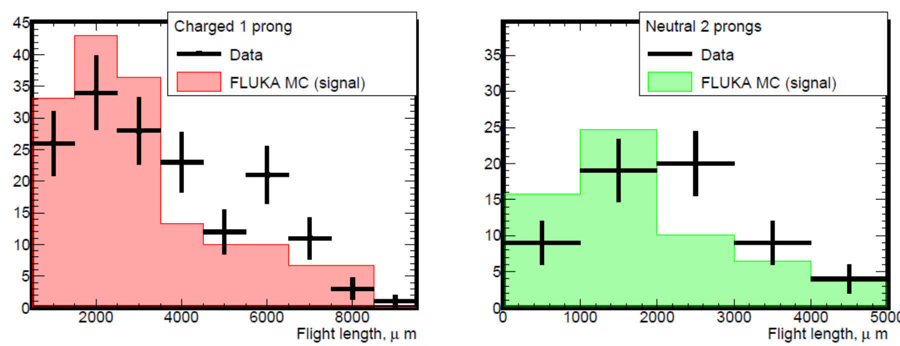
Pilot run analysis

- Full area of ~3000 emulsion films (~40 m²) scanned by the HTS-1.
- 400 GeV proton interactions and charm production being studied (aiming to study forward charm production).

Physics run in 2021-2022

- Beam characteristics being studied.
- Both molybdenum and tungsten will be used as target materials.
- **2.5×10^8 proton interactions and ~4×10^5 charm events** are expected in the physics run. **~1000 $D_s \to \tau \to X$ events will be detected** for the measurement of D_s differential production cross section.

159 double-charm candidates detected in the sub-sample



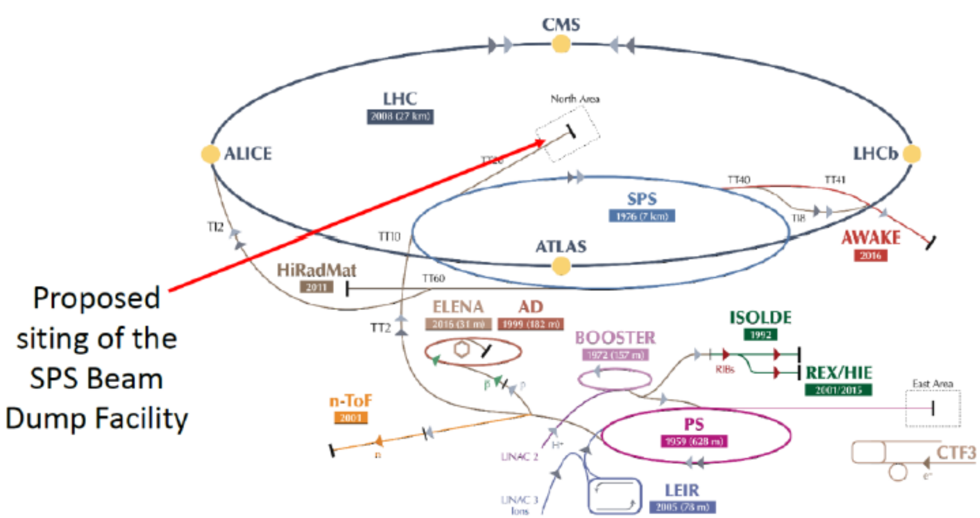
SHiP

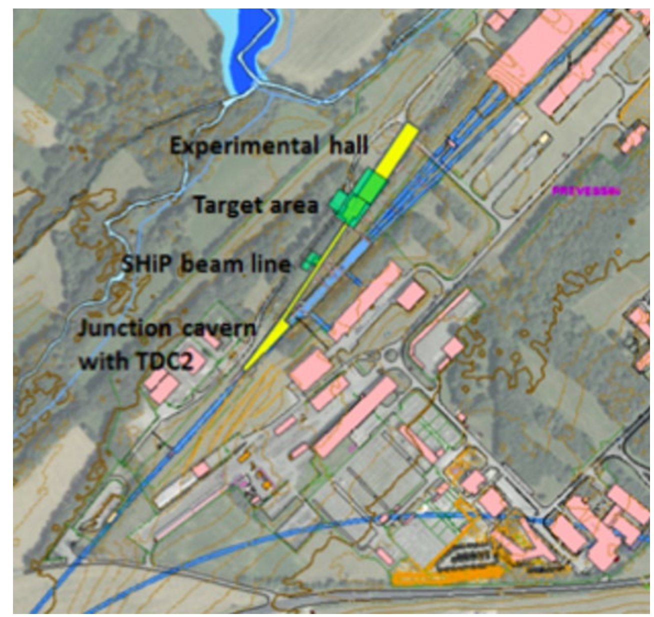
Thanks to
G. De Lellis,
M. Komatsu

- **A fixed target experiment proposal at the SPS**
  - Looking for new physics in intensity frontier
    - Technical Proposal in Apr. 2015, arXiv:1504.04956
    - Comprehensive Design Study Report in Dec. 2019

HNL searches will be covered by the next talk

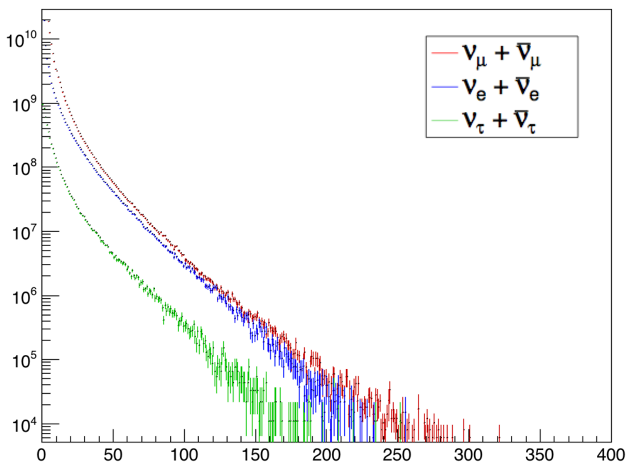
- **The SHiP facility**
  - CERN-based Beam Dump Facility (BDF)
  - Slow extraction (1 sec)
  - High intensity proton beam, 400 GeV/c
    - 4×10^{13} protons per spill, 2×10^{20} pot / 5 years



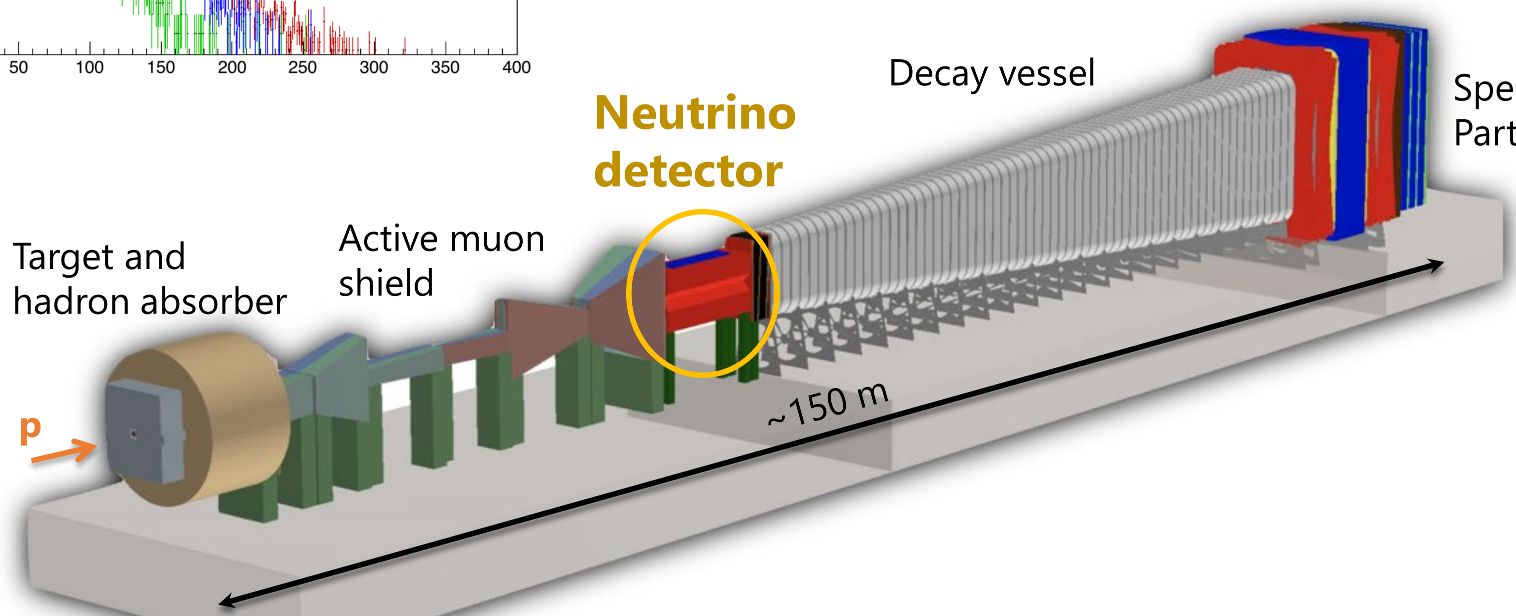


Neutrinos at SHiP

Neutrino energy spectrum @beam dump

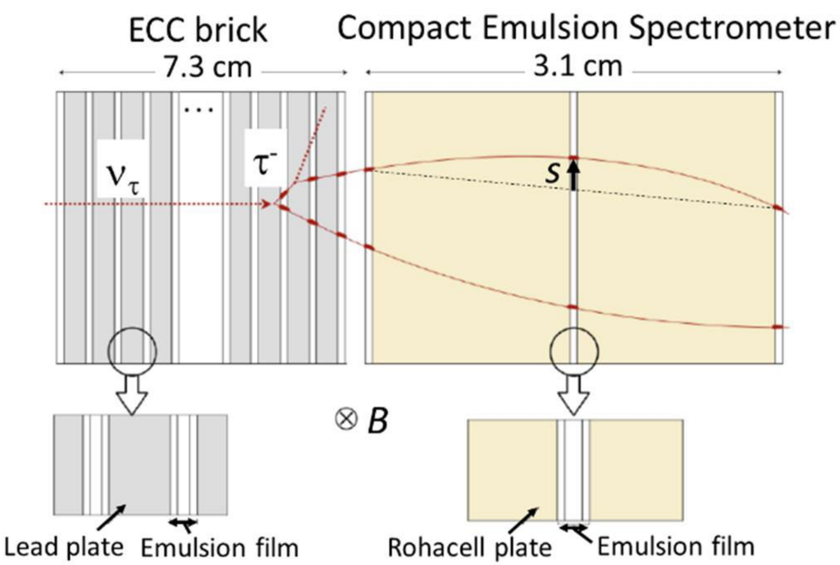


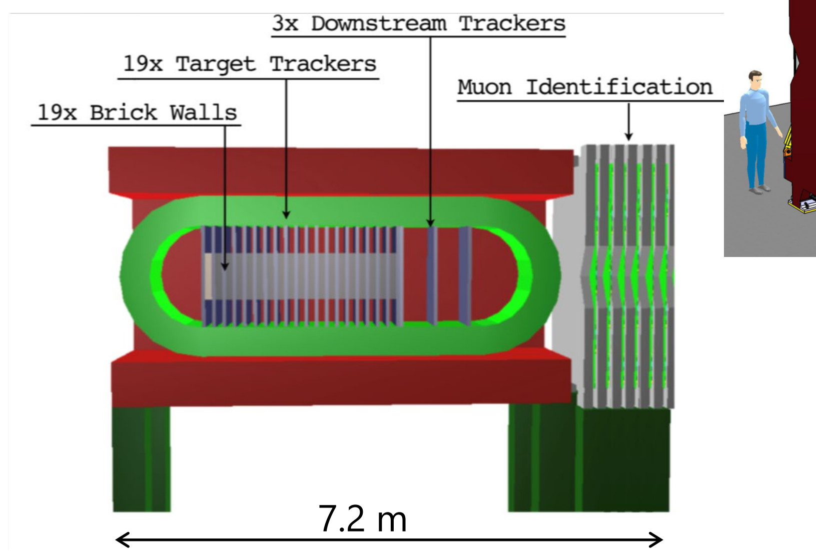
- **Neutrino physics potential**
  - Cross section measurements of all flavor of neutrinos
  - ν_τ and of $\bar{\nu}_\tau$ physics with high statistics
    - First detection of $\bar{\nu}_\tau$
  - ν induced charm production studies

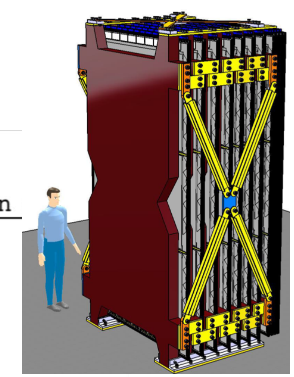


Scattering and Neutrino Detector (SND)

- **Experimental requirements**
  - Reconstruct ν interactions → Emulsion Cloud Chamber (ECC) technique + Target Tracker (TT)
  - Tag ν flavor → ECC technique + μ ID system
  - Tag ν and anti-ν → Magnetized target
- **SND magnetized target**
  - ECC brick: 57 emulsion films interleaved with lead plates, total target mass: ~8 tons
  - Followed by compact emulsion spectrometer, 1.2 T horizontal field
- **SciFi target tracker**
  - Provide time stamp and link muon track information from the target to the magnetic spectrometer
- **Muon ID system**
  - Iron absorbers, RPC as tracking detectors
  - Sensitive area of ~2×4 m^2

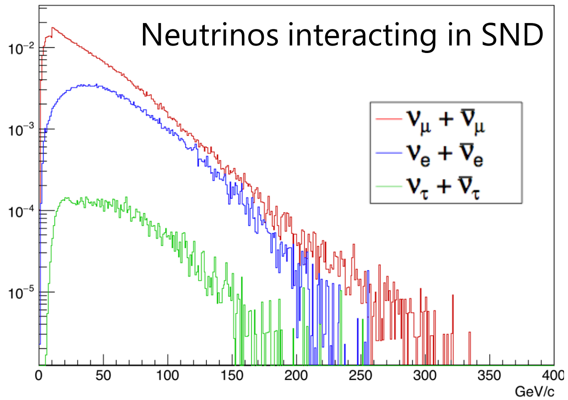






Neutrino physics prospects @BDF (1)

- **Huge neutrino flux**



Expected CC DIS interactions for 2x10^20 pot

	$\langle E \rangle$ [GeV]	CC DIS interactions
N_{ν_e}	59	1.1×10^6
N_{ν_μ}	42	2.7×10^6
N_{ν_τ}	52	3.2×10^4
$N_{\overline{\nu}_e}$	46	2.6×10^5
$N_{\overline{\nu}_\mu}$	36	6.0×10^5
$N_{\overline{\nu}_\tau}$	70	2.1×10^4

- **Measuring ν_τ and $\overline{\nu}_\tau$ cross sections**
  - Expectations in 5 years run
  - **~10000 signal events are expected to be detected**

Expected number of ν_τ and $\bar{\nu}_\tau$ signal events

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
Total	6200	4700

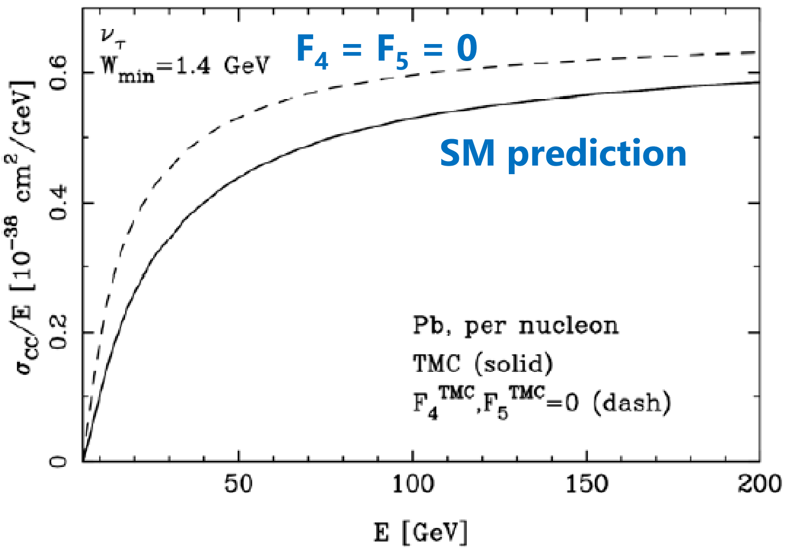
SHiP

Neutrino physics prospects @BDF (2)

- **First evaluation of F_4 and F_5**
  - Not accessible with other neutrinos

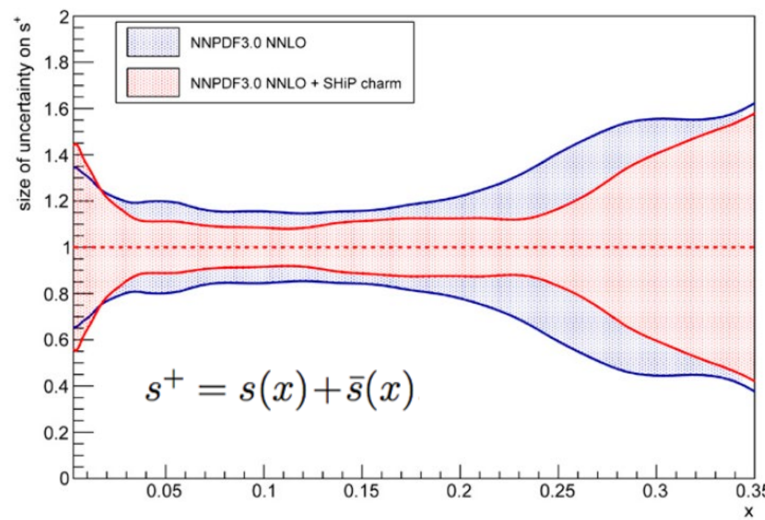
$$\frac{d^2\sigma^{\nu(\bar\nu)}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left(\left(y^2x + \frac{m_\tau^2 y}{2E_\nu M}\right)F_1 + \left[\left(1-\frac{m_\tau^2}{4E_\nu^2}\right) - \left(1+\frac{Mx}{2E_\nu}\right)y\right]F_2 \pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2M^2x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\right),$$

ν_τ CC DIS cross section



S. Alekhin et al., Rep. Prog. Phys. 79 (2016) 124201

- **ν induced charm production studies**
  - Understanding the strange quark nucleon content.
  - Anti-charm production in charged current anti-neutrino interactions selects anti-strange quark in the nucleon.
    - ~27000 events expected in SHiP



The reduction of the uncertainty is significant in the ranges 0.03–0.3 for s^+ (and 0.08–0.3 for s^-).

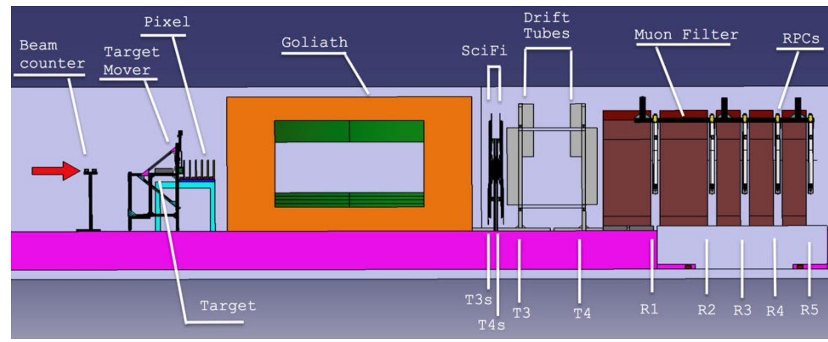
SHiP-charm project

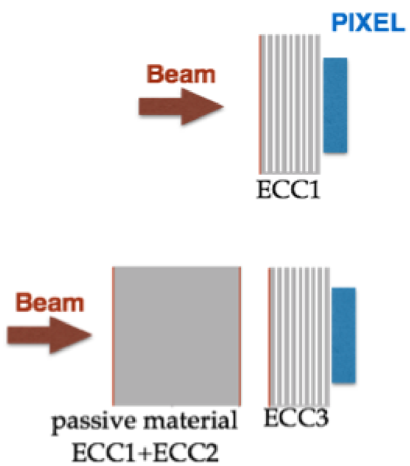
- SHiP-charm project aims at measuring the charm differential production cross section in the SHiP target, including cascade production with the 400 GeV/c proton beam

- **An optimization run was performed in July 2018** at the H4 beam line of the SPS
  - Proton target: emulsion-lead brick
  - 1.5×10^{6} pot integrated
  - A double-charm candidate event was detected

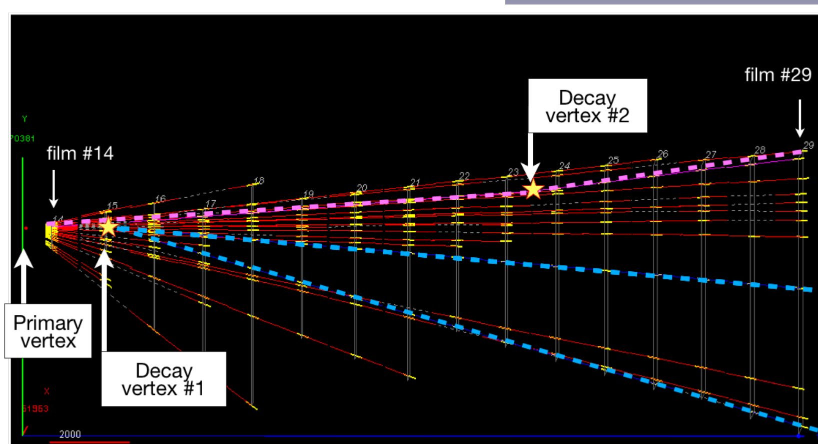
- **Another run** with larger statistics is planned after LS2
  - 5×10^{7} pot will be integrated
  - ~1000 fully reconstructed charm events are expected

Planned hybrid system, combining the emulsion technique with a spectrometer to provide the charge and momentum measurement of charmed hadron decay daughters and the muon identification





‣ **Double charm** decay topology



EVENT TOPOLOGY:

Primary vertex multiplicity: 31
Secondary vertices detected: 2

Decay vertex #1:
V0-like topology
- Number of prongs: 2
- Impact parameters to primary vtx: 594μm, 253 μm
- Flight length: 2.1 mm

Decay vertex #2:
kink-like topology
- Number of prongs: 1
- Kink angle: 31 mrad
- Flight length: 12.7 mm

Summary

- New experiments at the LHC will study high-energy neutrinos in unexplored energy regime (~TeV).
  - **FASERν**: Will measure neutrinos from a collider for the first time. ~10000 CC interactions (distinguishing the flavors) are expected in 2021-2024.
  - **XSEN, SND@LHC**: Aiming to measure ~2000 CC interactions (distinguishing the flavors) in 2022-2024.

- Fixed-target experiments at the SPS offers a unique opportunity for high-statistics tau-neutrino studies.
  - **SHiP neutrino program**: Aiming to detect ~10000 ν_τ and $\bar{\nu}_\tau$ CC interactions after LS3.
  - **NA65/DsTau**: Will study ν_τ production / forward charm production in 2021-2022.

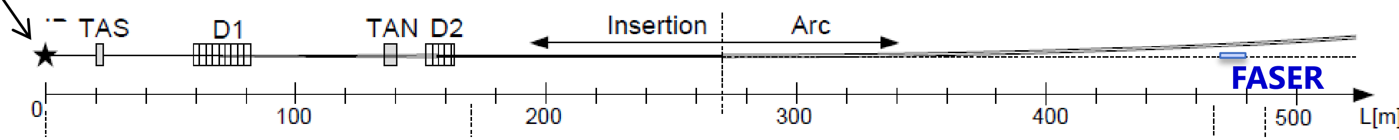
Backup slides

The FASER detector

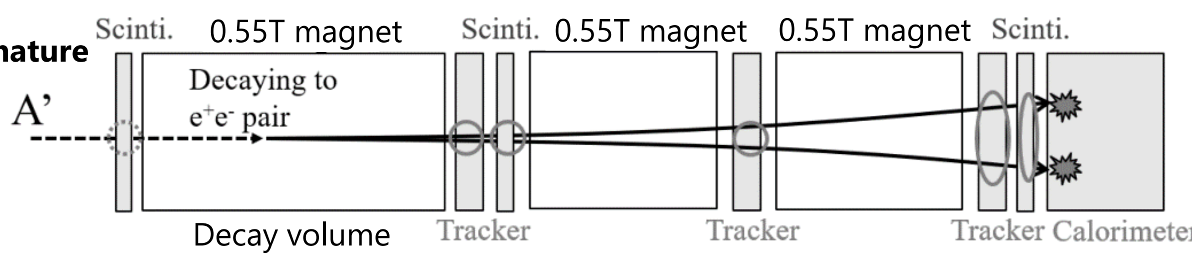
Technical proposal: FASER,
CERN-LHCC-2018-036 ; LHCC-P-013

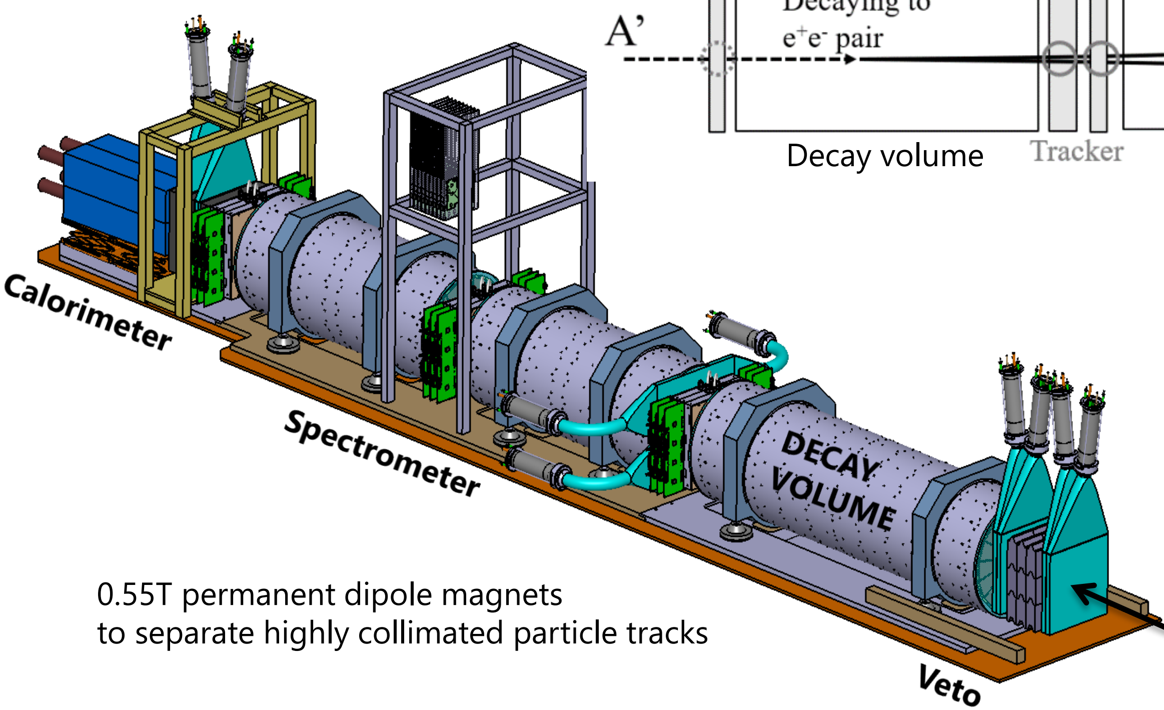
ATLAS interaction point

pp → LLP + X, LLP travels ~480 m, LLP → e^+e^-, $\mu^+\mu^-$, ...



Signal signature





0.55T permanent dipole magnets
to separate highly collimated particle tracks

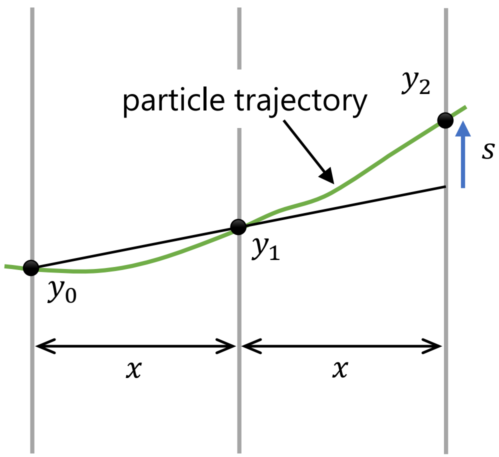
Incoming
particles

The detector consists of:
- Scintillator veto
- 1.5 m long decay volume
- 2 m long spectrometer
- EM calorimeter

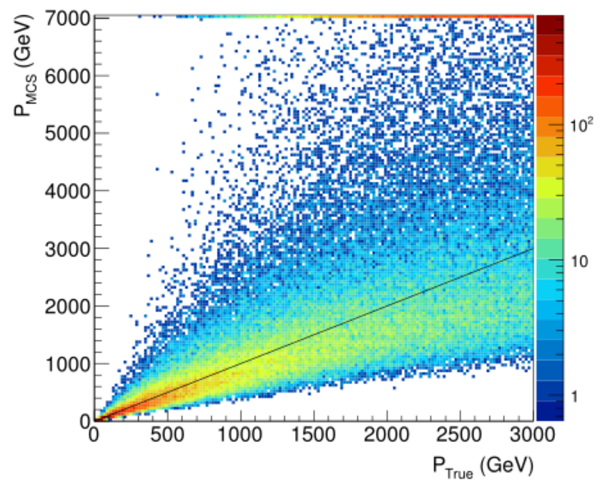
Particle momentum measurement

by multiple Coulomb scattering (MCS)

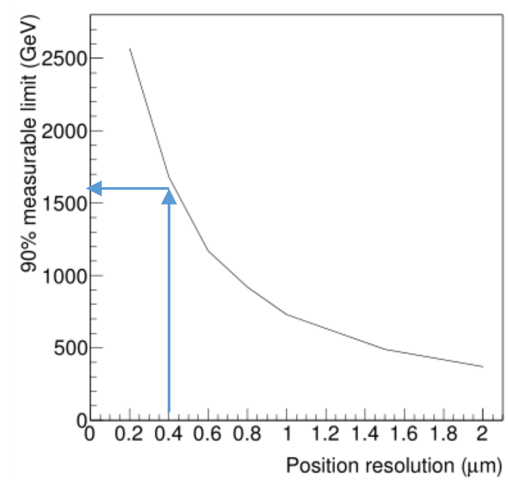
- Sub-micron precision alignment using muon tracks
  - Our experience = 0.4 μm (in the DsTau experiment)
- This allow to measure particle momenta by MCS, even above 1 TeV.



$$(s^{\mathrm{RMS}})^2 = \left(\sqrt{\frac{2}{3}}\frac{13.6(\mathrm{MeV})}{\beta P}x\sqrt{\frac{x}{X_0}}\right)^2 + \left(\sqrt{6}\,\sigma_{\mathrm{pos}}\right)^2$$



Performance with position resolution of 0.4 μm, in 100 tungsten plates (MC)



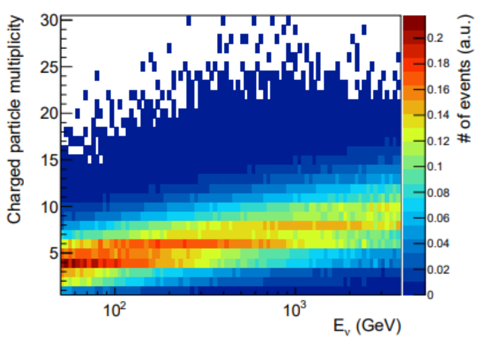
Measurable energy vs position resolution

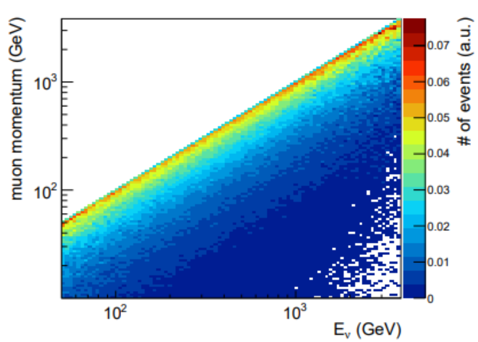
Neutrino energy reconstruction

- Neutrino energy will be reconstructed by combining topological and kinematical variables

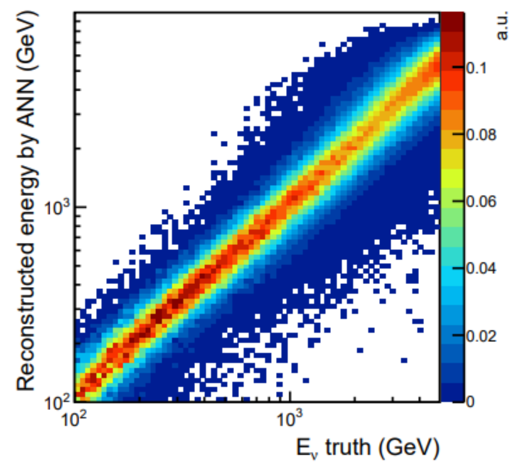
An ANN algorithm was built with
topological variables
- # of charged tracks → E_h
- # of γ showers → E_h
- inverse of lepton angle → E_l
- sum of inverse of hadron track angles → E_h
- inverse of median of all track angles → E_h, E_l

kinematical info (smeared)
- lepton momentum → E_l
- sum of charged hadron momenta → E_h
- sum of energy of γ showers → E_h





$E_\nu - E_{ANN}$



$$\frac{\Delta E}{E} \sim 30\%$$

Charmed particle differential production cross section results

DsTau NA65

$$\frac{d^2\sigma}{dx_F dp_T^2} \propto \underbrace{(1-|x_F|)^n}_{\text{longitudinal dependence}} \underbrace{\exp(-bp_T^2)}_{\text{transverse dependence}}$$

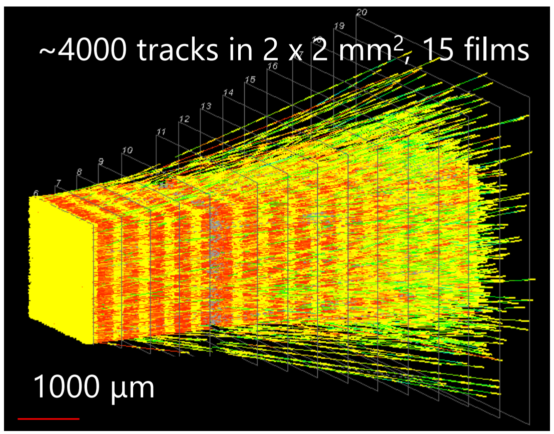
- **No experimental result effectively constraining the D_s differential cross section** at the desired level or consequently the ν_τ production

Experiment	Beam type / energy (GeV)	$\sigma(D_s)$ (μb/nucl)	$\sigma(D^\pm)$ (μb/nucl)	$\sigma(D^0)$ (μb/nucl)	$\sigma(\Lambda_c)$ (μb/nucl)	x_F and p_T dependence: n and b (GeV/c)$^{-2}$
HERA-B	p / 920	18.5 ± 7.6 (~11 events)	20.2 ± 3.7	48.7 ± 8.1	-	$n(D^0, D^+)$ = 7.5 ± 3.2
E653	p / 800	-	38 ± 17	38 ± 13		$n(D^0, D^+) = 6.9^{+1.9}_{-1.8}$ $b(D^0, D^+) = 0.84^{+0.10}_{-0.08}$
E743 (LEBC-MPS)	p / 800	-	26 ± 8	22 ± 11		$n(D)$ = 8.6 ± 2.0 $b(D)$ = 0.8 ± 0.2
E781 (SELEX)	Σ^- (sdd) / 600					~350 D_s^- events, ~130 D_s^+ events (x_F>0.15) $n(D_s^-)$ = 4.1 ± 0.3 (leading effect) $n(D_s^+)$ = 7.4 ± 1.0
NA27	p / 400		12 ± 2	18 ± 3		
NA16	p / 360		5 ± 2	10 ± 6		
WA92	π / 350	1.3 ± 0.4		8 ± 1		
E769	p / 250	1.6 ± 0.8	3 ± 1	6 ± 2		320 ± 26 events ($D^\pm$, D^0, $D_s^\pm$) $n(D^\pm, D^0, D_s^\pm)$ = 6.1 ± 0.7 $b(D^\pm, D^0, D_s^\pm)$ = 1.08 ± 0.09
E769	$\pi^\pm$ / 250	2.1 ± 0.4		9 ± 1		1665 ± 54 events ($D^\pm$, D^0, $D_s^\pm$) $n(D^\pm, D^0, D_s^\pm)$ = 4.03 ± 0.18 $b(D^\pm, D^0, D_s^\pm)$ = 1.08 ± 0.05
NA32	π / 230	1.5 ± 0.5		7 ± 1		

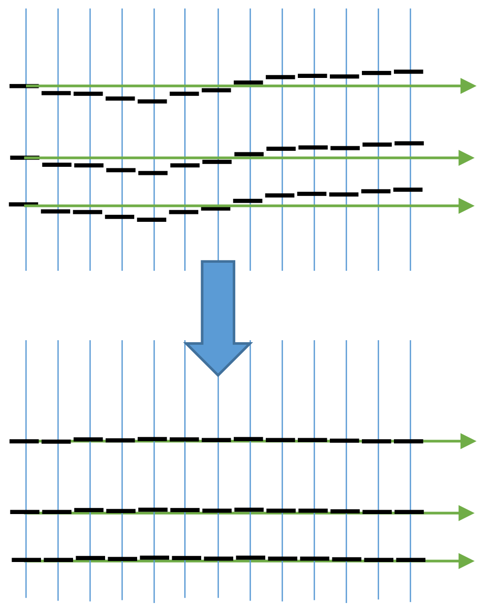
Results from LHCb at $\sqrt{s}$ = 7, 8 or 13 TeV are not included since the energies differ too much.

Angular resolution

Reconstructed tracks

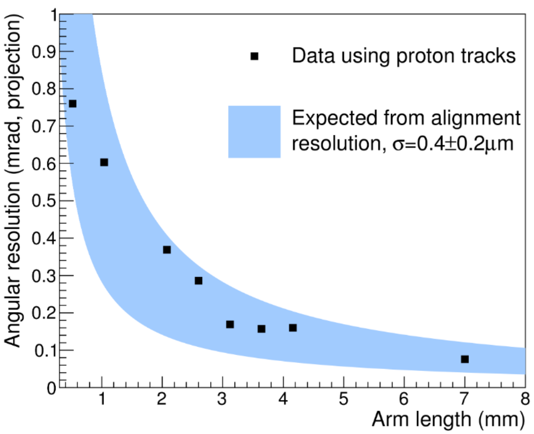


Align films with proton tracks (100 tracks/mm²)



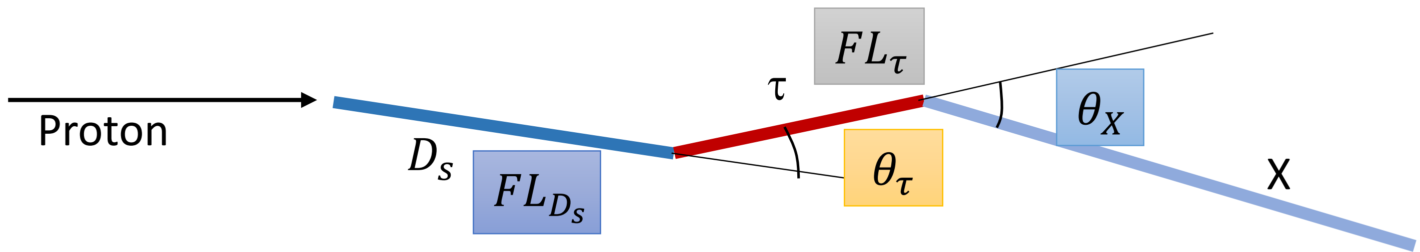
Residual of track segments to fitted line (RMS) ≃ **0.4 µm**

Angular resolution vs track length



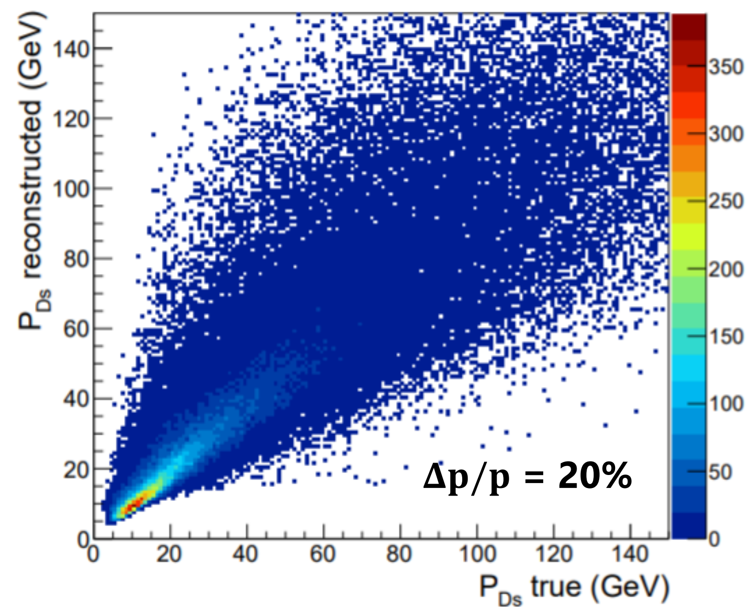
D_s momentum reconstruction

by Artificial Neural Network using topological variables



FL: flight length

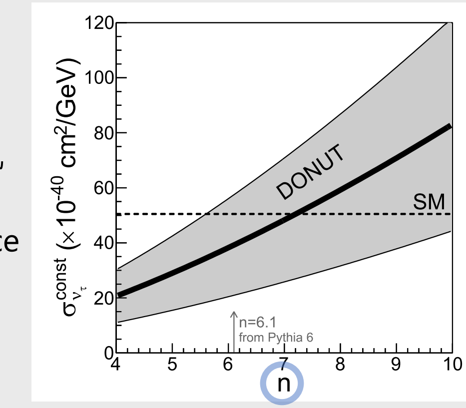
- Difficult to measure D_s momentum directly due to short lifetime
- → D_s momentum reconstruction by topological variables
- A Neural Network with 4 variables was trained with MC events
- Momentum resolution $\Delta p/p$ = 20%



Expected precision of D_s differential cross-section measurement

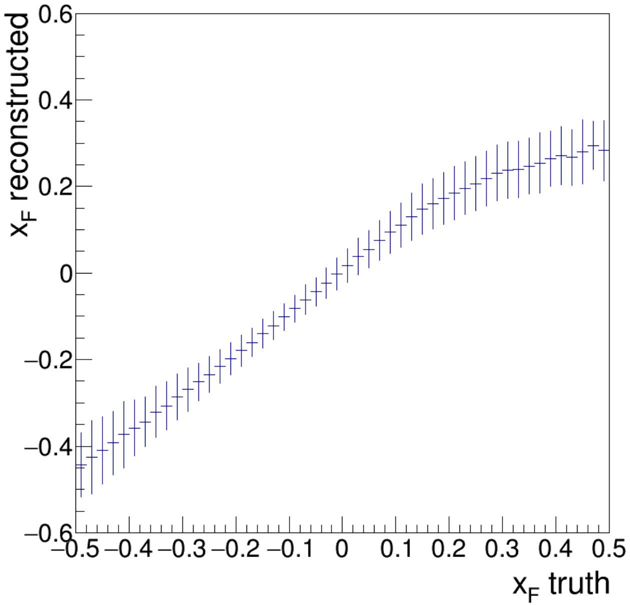
Parametrization used in DONuT

$$\frac{d^2\sigma}{dx_F\,dp_T^2} \propto \underbrace{(1-|x_F|)^n}_{\text{longitudinal dependence}}\ \underbrace{\exp(-bp_T^2)}_{\text{transverse dependence}}$$

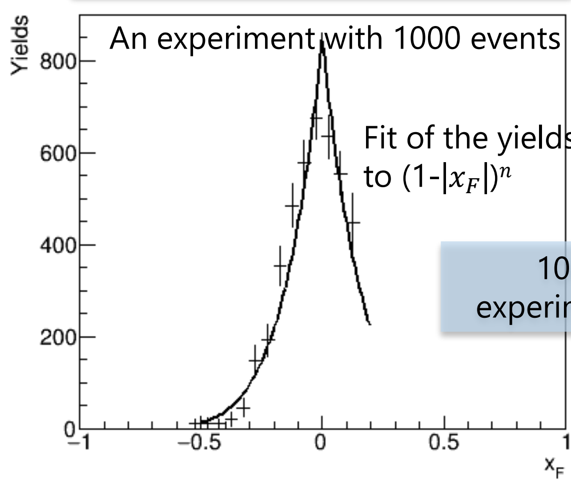


x_F : longitudinal profile of D_s

$x_F = 2p_z^{CM}/\sqrt{s} = 2\gamma(p_{D_s}^{Lab}\cos\theta_{D_s} - \beta E_{D_s}^{Lab})/\sqrt{s}$

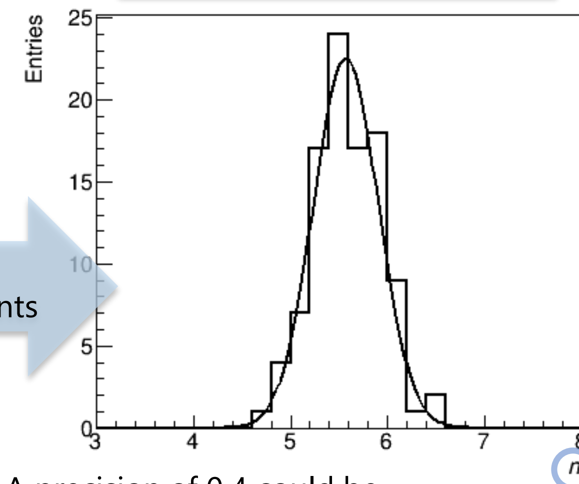


Reconstructed x_F
(corrected by the efficiency)



100 experiments

Estimated parameter n



A precision of 0.4 could be achieved using 1000 events