Neutrino projects with nuclear emulsion

Tomoko Ariga (Kyushu University)

on behalf of the B02 group

Neutrino projects with emulsion detectors

Emulsion technologies

Emulsion hardware

Automated scanning system

Ongoing projects

NINJA at J-PARC	EMPHATIC at FNAL	SHiP at CERN SPS	DsTau at CERN SPS	FASERν at CERN LHC
• Precise measurement of ν_μ and ν_e interactions	• Precise measurement of hadron production	• Study of tau-neutrino interactions (~10000 ν_τ and anti-ν_τ interactions)	• Measurement of tau-neutrino production	• Study of TeV neutrinos • Tau-neutrino cross section at the highest energy ever

Study of tau neutrinos

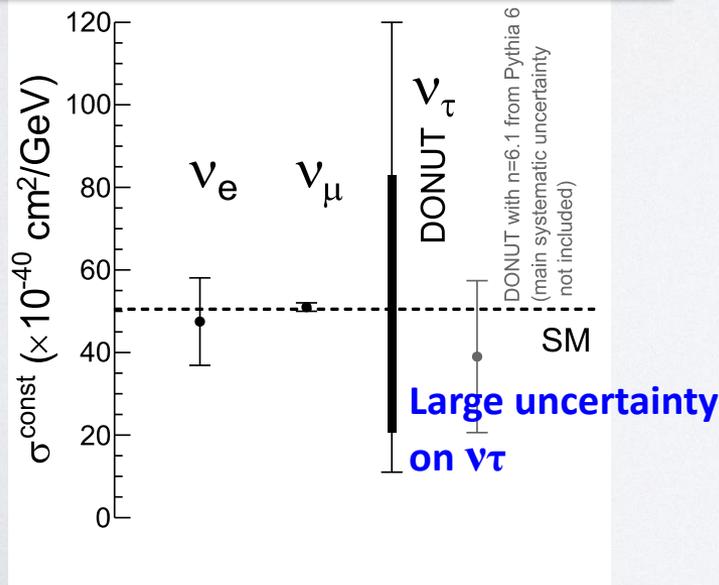- Tau neutrino is one of the least studied particles
  - Only a few measurements   Direct ν_τ beam: **DONuT**

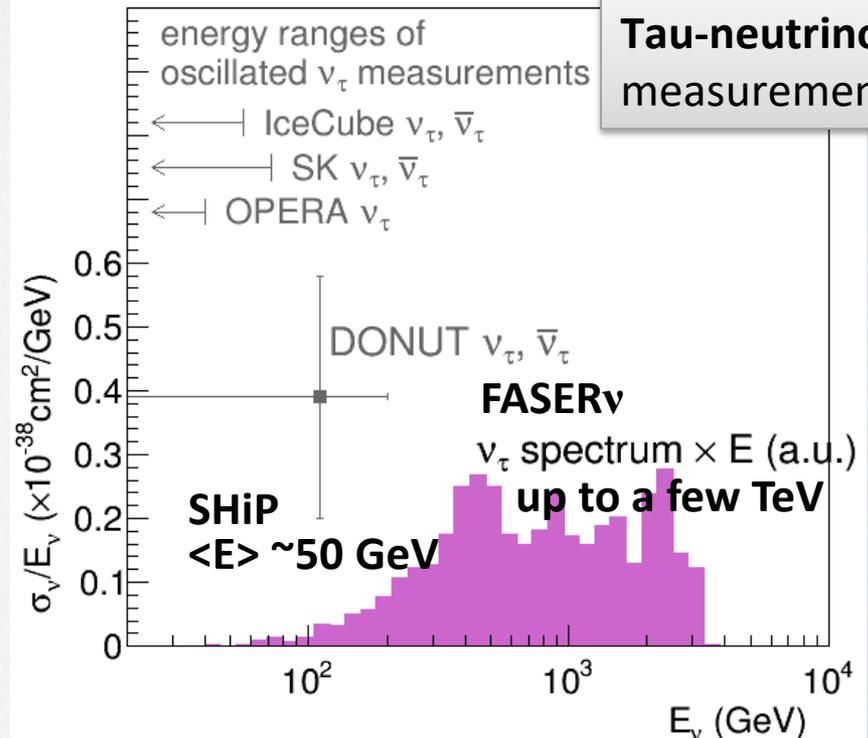   Oscillated ν_τ: **OPERA**, **Super-K**, **IceCube**

- Physics motivations

  - **Test of lepton universality** in tau-neutrino interactions
  - **Search for new physics effects**
    - e.g. flavor anomaly involving heavy leptons and quarks -> study of neutrino CC interaction with heavy quark production could be a complementary approach

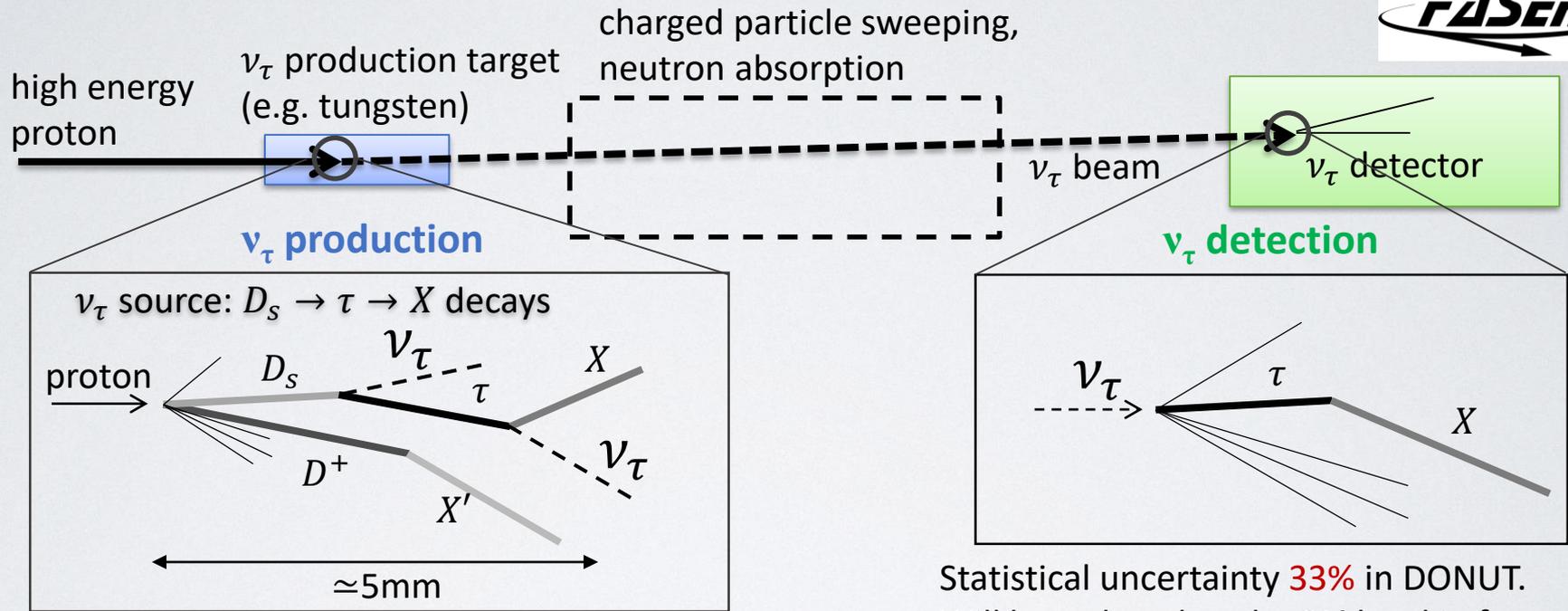Energy independent cross section of the three neutrino flavors (in high-energy region)

Tau-neutrino measurements

Concept of ν_τ cross section measurement

high energy proton

ν_τ production target (e.g. tungsten)

charged particle sweeping, neutron absorption

ν_τ beam

ν_τ detector

ν_τ production

ν_τ source: $D_s \rightarrow \tau \rightarrow X$ decays

proton
D_s
ν_τ
τ
X
D^+
ν_τ
X'

$\simeq 5\text{mm}$

ν_τ detection

ν_τ
τ
X

Statistical uncertainty 33% in DONUT. Will be reduced to the **2%** level in future experiments.

Large systematic uncertainty (~50%) in the ν_τ flux prediction
→

DsTau (CERN SPSC-P-354)

SHiP (CERN SPSC-P-350)

FASERν (neutrinos from LHC)

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SHiP neutrino program

SHiP Collaboration
~250 collaborators, 57 institutes
(Aichi, Kobe, Nagoya, Nihon, Toho from Japan)

- SHiP was proposed to look for new physics in intensity frontier

- Neutrino program
  - Studying tau-neutrino interactions (~10000 ν_τ and anti-ν_τ interactions!)
  - Neutrino induced charm production

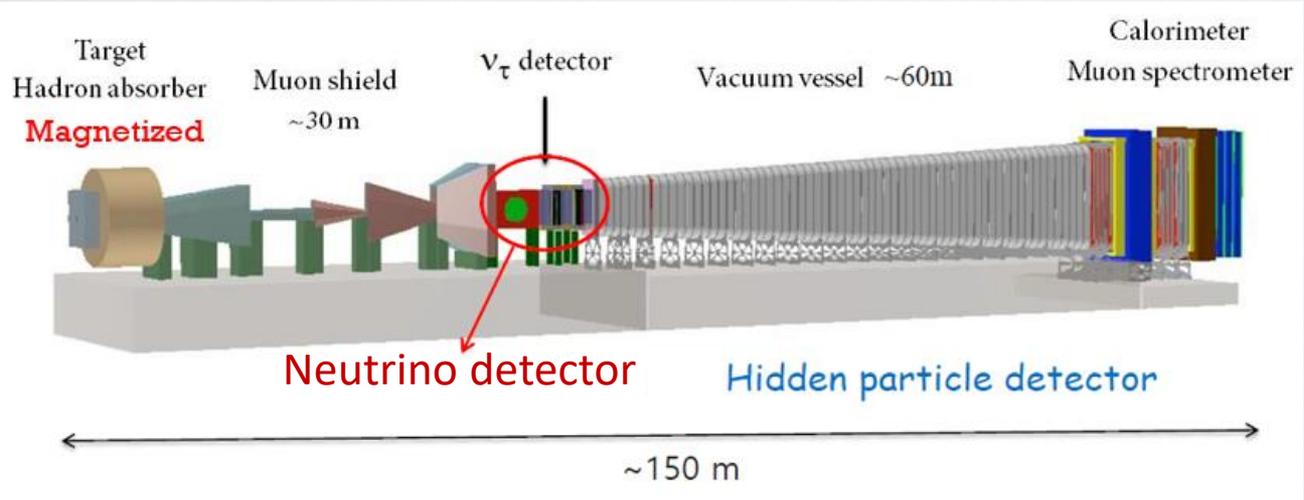**Expected CC DIS interactions in the detector for 2×10^{20} pot**

	$<E>[\,GeV\,]$	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
$N_{\bar{\nu}_e}$	46	2.6×10^5
$N_{\bar{\nu}_\mu}$	36	6.0×10^5
$N_{\bar{\nu}_\tau}$	70	2.1×10^4

Expected tau-neutrino events (detected)

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

Target
Hadron absorber
Magnetized
Muon shield ~30 m
ν_τ detector
Vacuum vessel ~60m
Calorimeter
Muon spectrometer
Neutrino detector
Hidden particle detector
~150 m

SHiP neutrino detector

ECC + Emulsion spectrometer

ECC brick 7.3 cm — Compact Emulsion Spectrometer 3.1 cm

ν_τ — τ^- — S — $\otimes B$

Lead plate, Emulsion film — Rohacell plate, Emulsion film

Test beam data

Entries 45315

6GeV/c π^- — 6GeV/c π^+
2GeV/c π^+ — 2GeV/c π^+

sx[μm]

Muon Filter

Brick Walls x 19 — Target Trackers x 19 — Spectrometer Planes x 3

30 cm — 160 cm — 340 cm — 491 cm

321 cm

700 cm

ν — ν_τ — τ^- — μ^- — ν
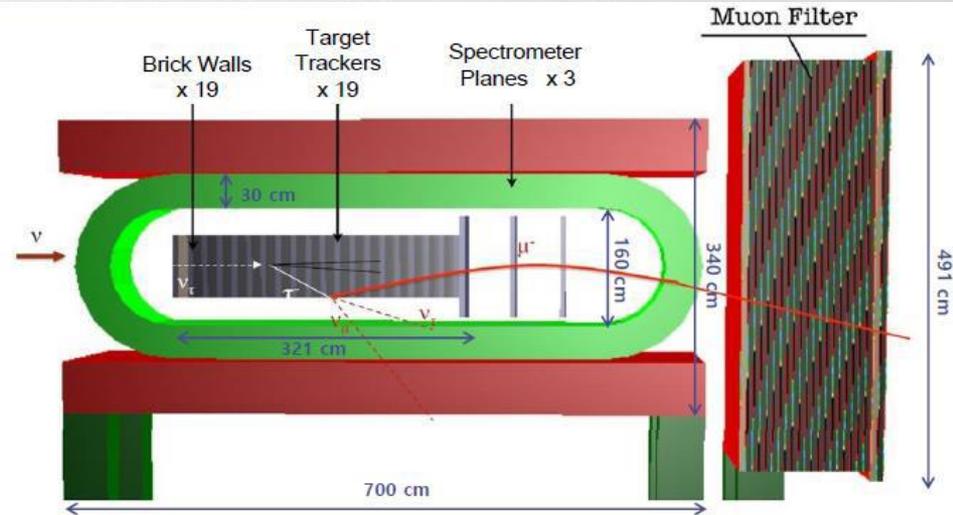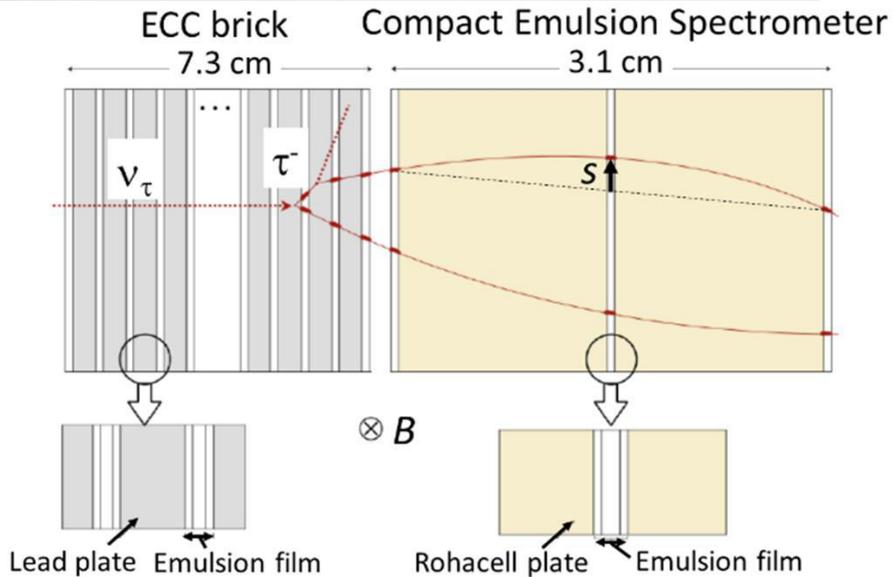
Emulsion films : High spatial resolution to observe the τ decay (~1 mm)
Target tracker (TT) : Electronic detector to predict ECC brick contained
ν interaction and provide the time stamp
Magnet : magnetized target to measure the charge of τ products
Spectrometer (CES) : Compact Emulsion Spectrometer to measure muon
momentum & charge
Muon filter (RPC) : Muon identification
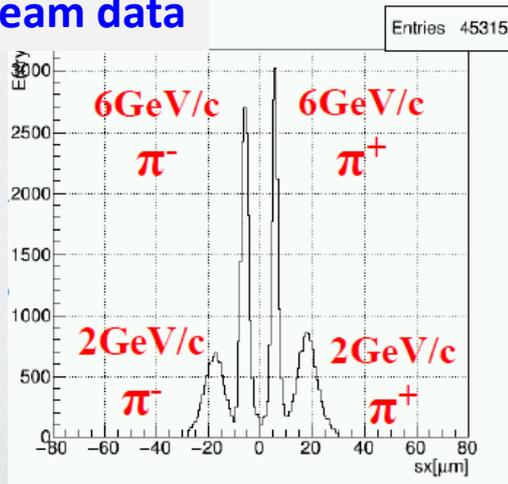
Plan of data taking:
5 years from 2026 (or later)
Emulsion ~7000 m^2, Target 7.6 ton
2x10^{20} pot, ~10000 ν_τ and anti-ν_τ int.
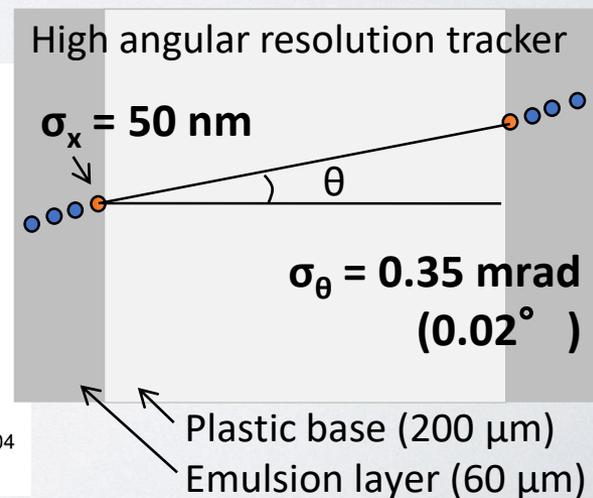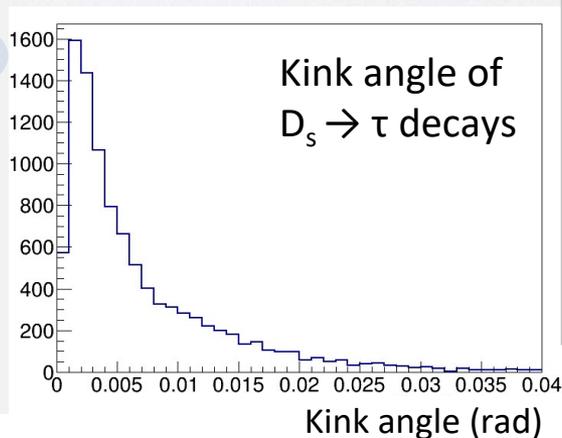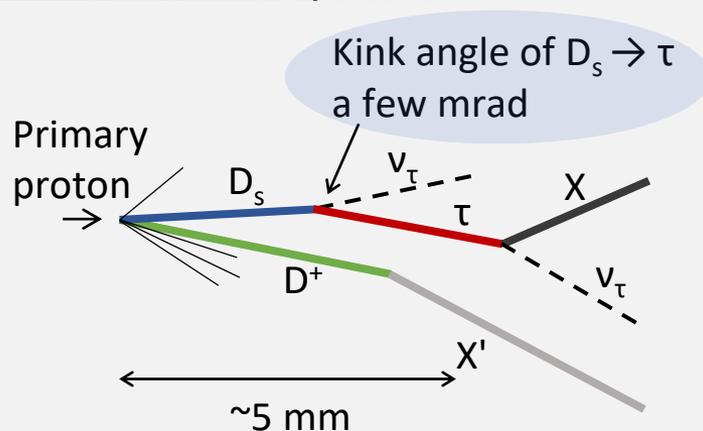
The DsTau project

DsTau Collaboration
~20 collaborators from Japan (Aichi, Kobe, Kyushu, Nagoya), Romania, Russia, Switzerland, Turkey

- **Physics goals**
  - Measurement of $\nu\tau$ production
    - **Measurement of Ds differential production cross section**
    - Reduction of systematic uncertainty in the cross section measurement 50% → 10%
    - **Important input for future $\nu\tau$ experiment**: SHiP $\nu\tau$ program
  - By-products: Forward charm production / intrinsic charm contribution
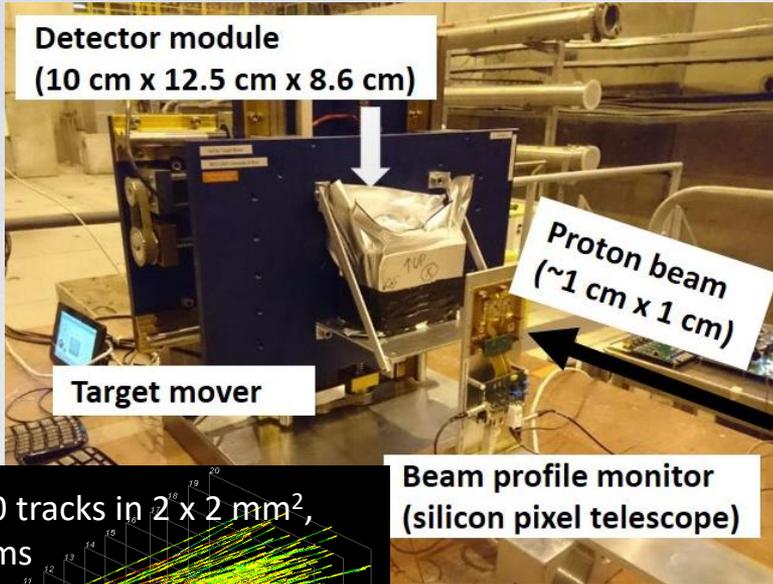
- **Principle of the experiment**
  - Detection of double-kink + charm decay topology within some mm
  - 4.6×10^9 protons, 2.3×10^8 proton interactions in tungsten, 10^5 charm pairs, 1000 $Ds \to \tau \to X$ decays

Kink angle of $D_s \to \tau$ a few mrad

Primary proton

D_s

ν_τ

τ

X

D^+

ν_τ

X'

~5 mm

Kink angle of $D_s \to \tau$ decays

Kink angle (rad)

High angular resolution tracker

σ_x = 50 nm

θ

σ_θ = 0.35 mrad (0.02°)

Plastic base (200 µm)
Emulsion layer (60 µm)

DsTau: status and prospect

Setup at the CERN SPS H4 beamline

Detector module
(10 cm x 12.5 cm x 8.6 cm)

Proton beam
(~1 cm x 1 cm)

Target mover

Beam profile monitor
(silicon pixel telescope)

~4000 tracks in 2 x 2 mm², 15 films

1000 μm

Data (sub-sample)

~5.6×10^6 protons analyzed → 20 charm candidate events

Flight length distributions

Charged 1 prong
— FLUKA MC (signal)
—●— Data
Flight length (μm)

Neutral 2 prong
— FLUKA MC (signal)
—●— Data
Flight length (μm)

kink

neutral decay

primary vertex

400 GeV proton

500 μm
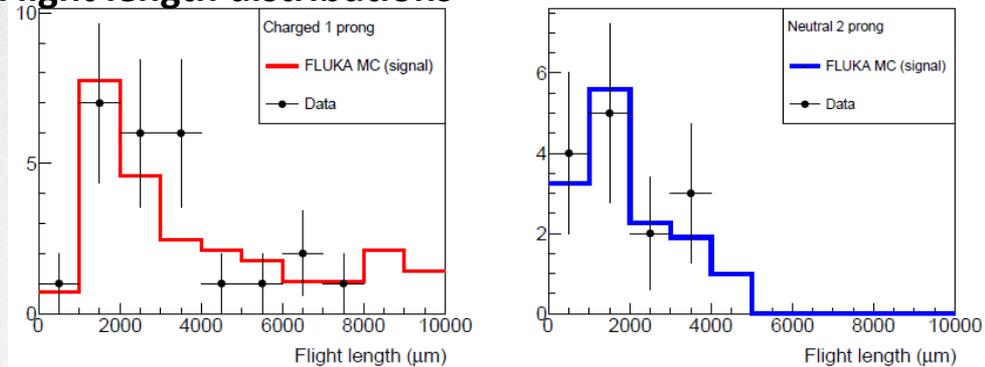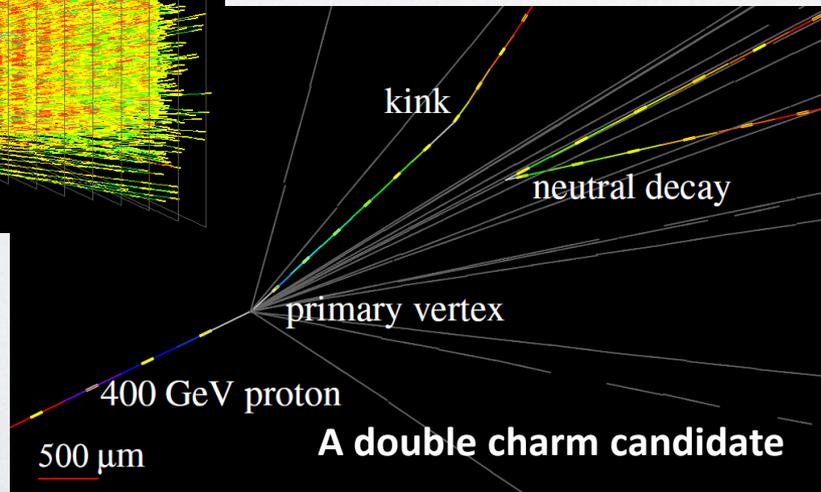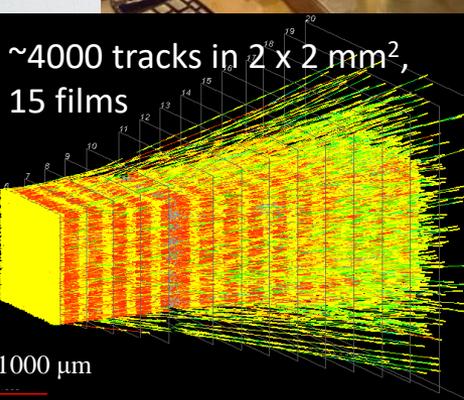
A double charm candidate

Physics run
in 2021-2022

pilot run

2021 run

2022 run

Expected precision of n

Relative uncertainty to ν_τ flux

Number of detected events

FASER: Forward Search Experiment at the LHC

- Designed to search for light, weakly interacting particles at the LHC
  - Such particles are dominantly produced at low p_T, may be long-lived and highly collimated → FASER
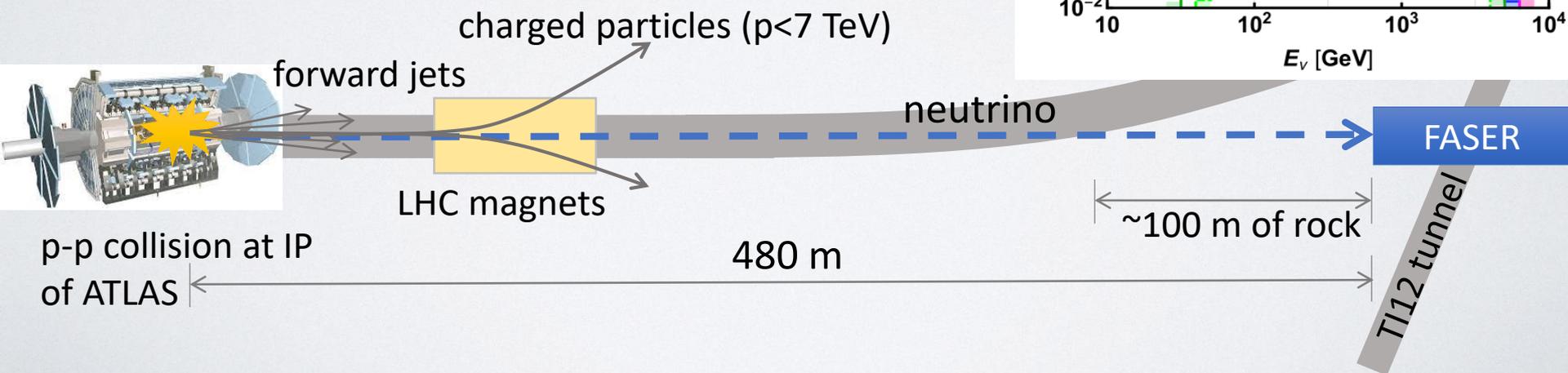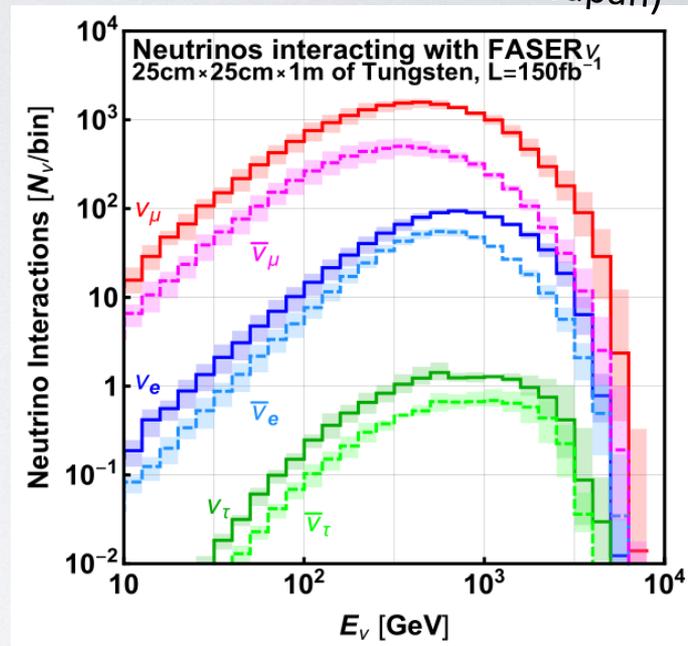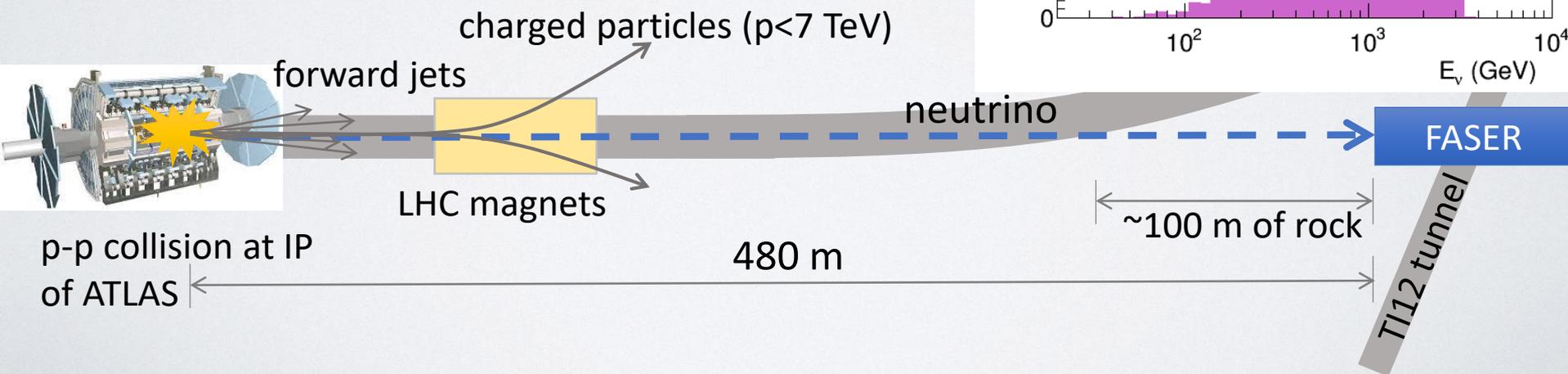
  FASER LOI and TP submitted in 2018.
  Approved by the CERN Research Board in March 2019

- FASER was approved for BSM searches, however the collaboration is actively studying possible neutrino measurements → FASERν

FASER Collaboration
~40 collaborators, 16 institutes
(KEK, Kyushu, Nagoya from Japan)

Neutrinos interacting with FASERν
25cm×25cm×1m of Tungsten, L=150fb^{-1}

charged particles (p<7 TeV)

forward jets

neutrino

FASER

LHC magnets

~100 m of rock

Tl12 tunnel

p-p collision at IP of ATLAS

480 m

FASER: Forward Search Experiment at the LHC

- Designed to search for light, weakly interacting particles at the LHC
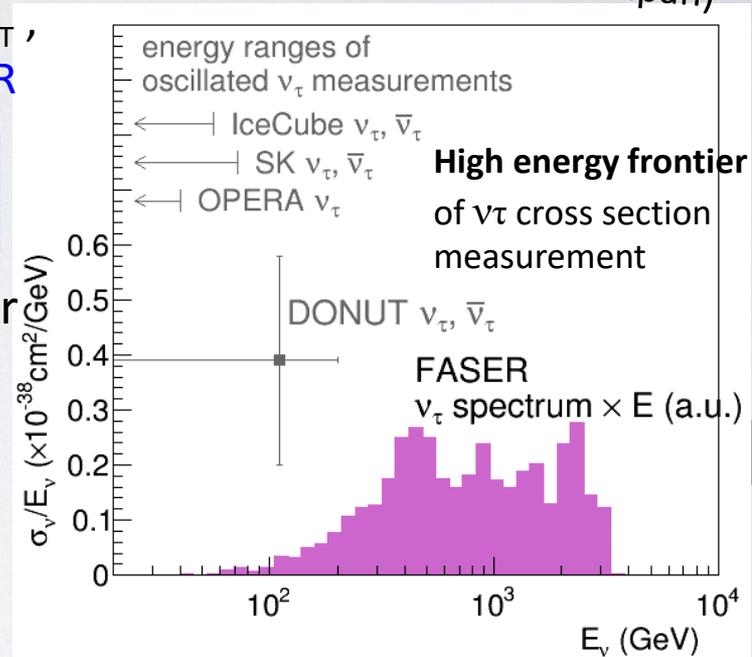 - Such particles are dominantly produced at low p_T, may be long-lived and highly collimated → FASER

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FASER Collaboration
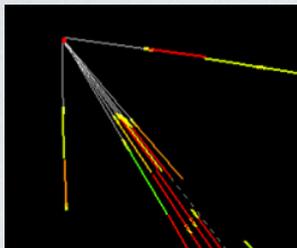~40 collaborators, 16 institutes
(KEK, Kyushu, Nagoya from Japan)

High energy frontier of ντ cross section measurement

charged particles (p<7 TeV)

forward jets

neutrino

FASER

LHC magnets

~100 m of rock

p-p collision at IP of ATLAS

480 m

Tl12 tunnel

FASERν detector design and plans

Emulsion detector worked in the 2018 test run!
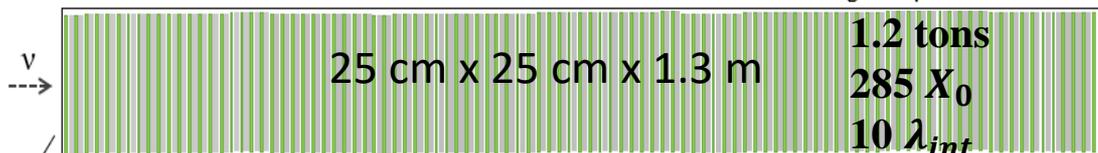
30 kg detector installed in 2018

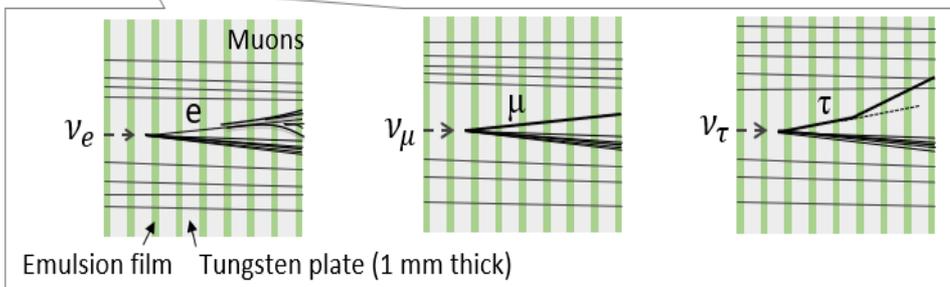line of sight

Detector setup for LHC run3

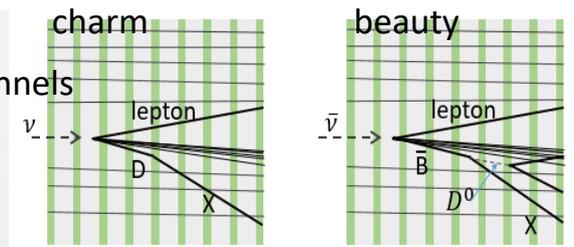Total 1000 emulsion films interleaved with 1-mm-thick tungsten plates

ν →

25 cm x 25 cm x 1.3 m

1.2 tons
285 X_0
10 λ_{int}

Detector surface
25 cm x 25 cm

Muons

$\nu_e \rightarrow$ e

$\nu_\mu \rightarrow$ μ

$\nu_\tau \rightarrow$ τ

Emulsion film   Tungsten plate (1 mm thick)

Heavy quark production channels

charm

beauty

ν ---> lepton
D
X

ν̄ ---> lepton
B̄
D^0
X

Possibly coupled with the FASER spectrometer

Expected performance:

Neutrino energy reconstruction by combining topological and kinematical variables

$$E_\nu - E_{ANN}$$

For ν_μ CC (GENIE)

$$\frac{\Delta E}{E} = 25\%(RMS)$$
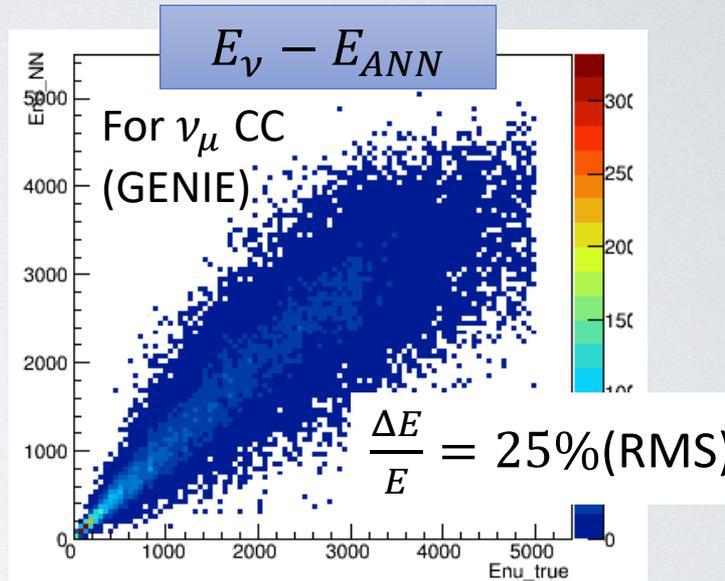
Expected yields in Run 3 (2021-2023)

	# of CC interactions in 1.2 ton detector	Mean interacting energy
$\nu_e + \bar{\nu}_e$	1296	827 GeV
$\nu_\mu + \bar{\nu}_\mu$	20439	631 GeV
$\nu_\tau + \bar{\nu}_\tau$	21	965 GeV

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The NINJA experiment

NINJA Collaboration
~40 collaborators from ICRR, Kobe, Kyoto, Nagoya, Nihon, Toho, Tokyo, Yokohama
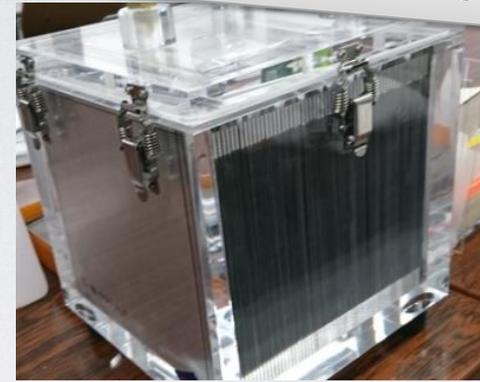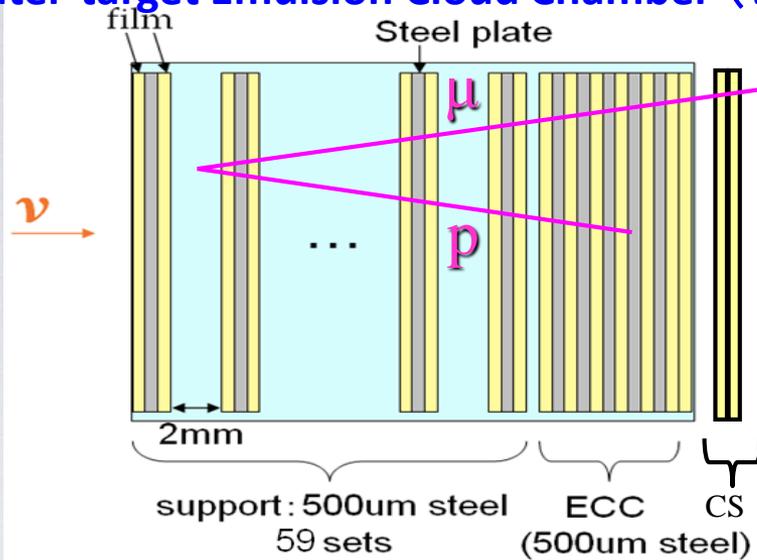
- Physics / goals
  - Study of sub-multi GeV neutrino – water interactions
    - Confirmation and cross-section measurement of 2p2h interactions
    - Exclusive cross-section measurements of ν_μ and ν_e
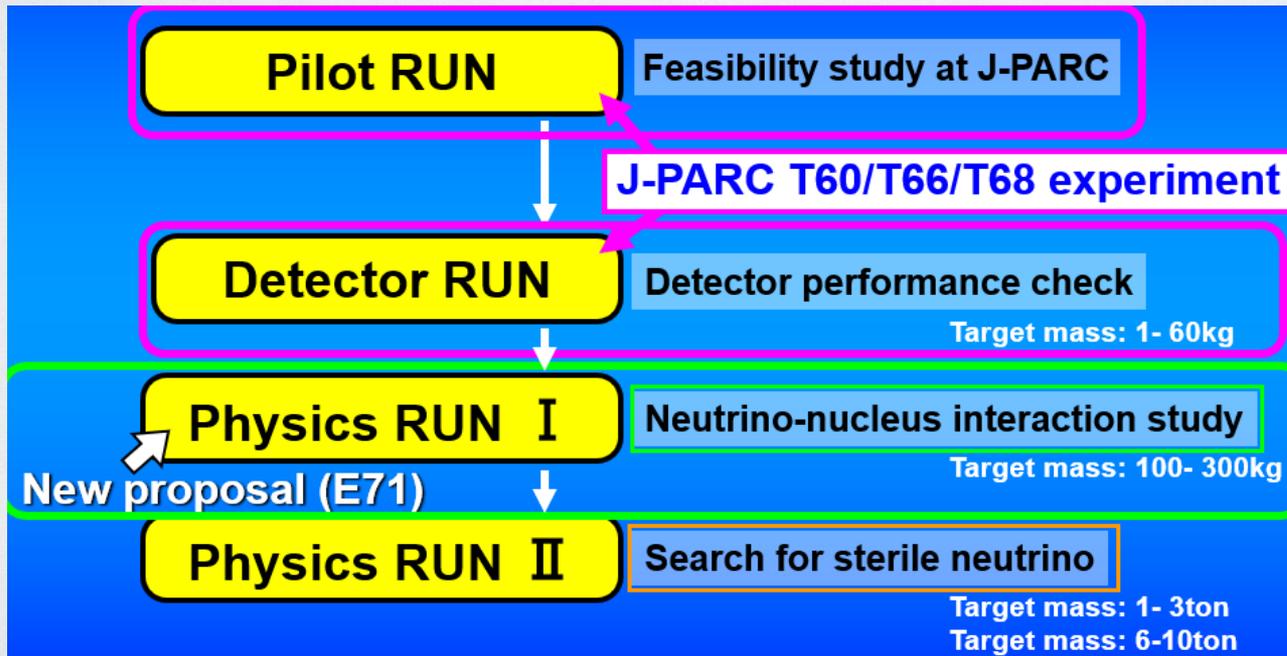
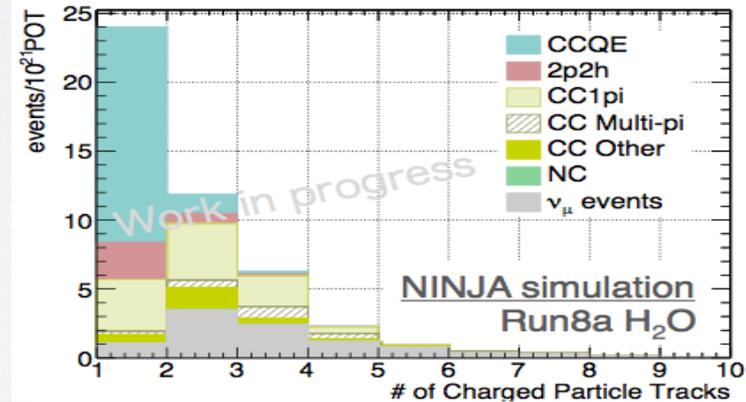# NINJA detector and analysis

NINJA talk in the A02 session

Water-target Emulsion Cloud Chamber（Water ECC）

Detector run (anti-neutrino mode)
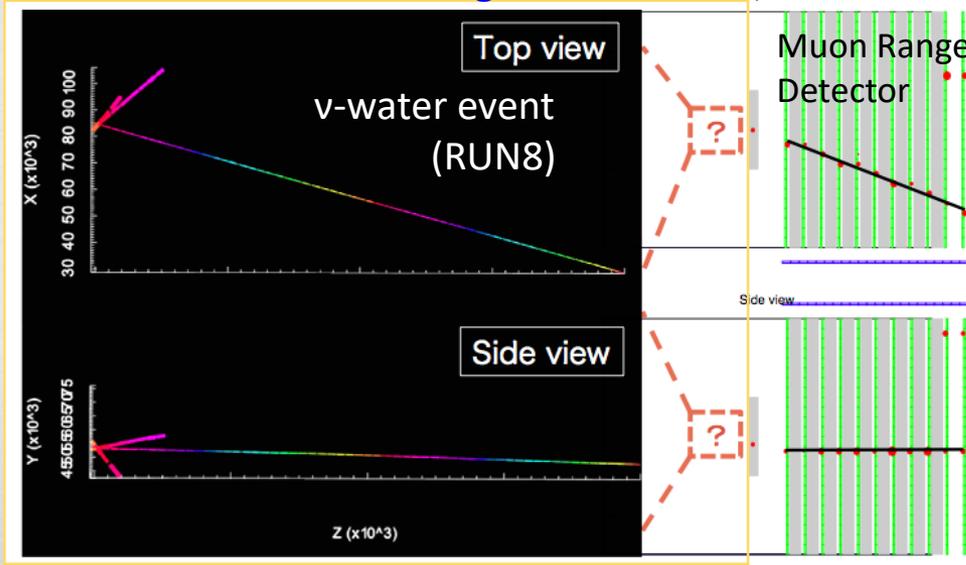
Charged track multiplicity (μ,p,π) of CC event

MC

Work in progress

NINJA simulation
Run8a H$_2$O

- CCQE
- 2p2h
- CC1pi
- CC Multi-pi
- CC Other
- NC
- ν_μ events

Emulsion – counter matching with emulsion shifter / SFT

Top view

ν-water event
(RUN8)

Side view

Muon Range Detector

Data **(work in progress)**

# of tracks	1	2	3	4	>5
candidates	59	11	4	0	0

13
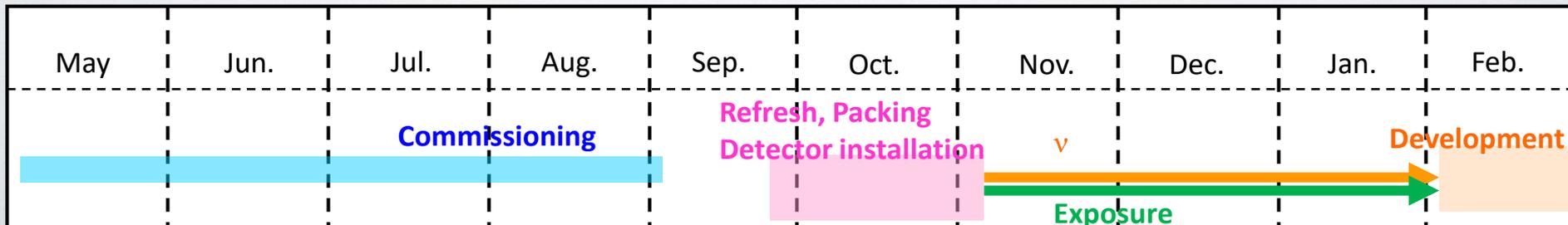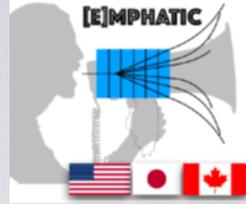
NINJA physics run in 2019

- Study of neutrino – water interactions with large statistics
- Hybrid plan with WAGASCI is in progress

Detector setup @B2 floor

Setup 7

60°
40°
30°
0°

Wall

SideMRD

30cm

195cm
BM tracker Height

BabyMIND

290 cm

BM tracker

WG   PM   NJ   WG

30cm

SideMRD

80cm   250kg Target

H_2O：75kg
Fe：130kg
CH：15kg
em：30kg

南
東 ← → 西
北

NINJA

Wall

E71a schedule

May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.

Commissioning

Refresh, Packing
Detector installation

ν

Exposure

Development

14
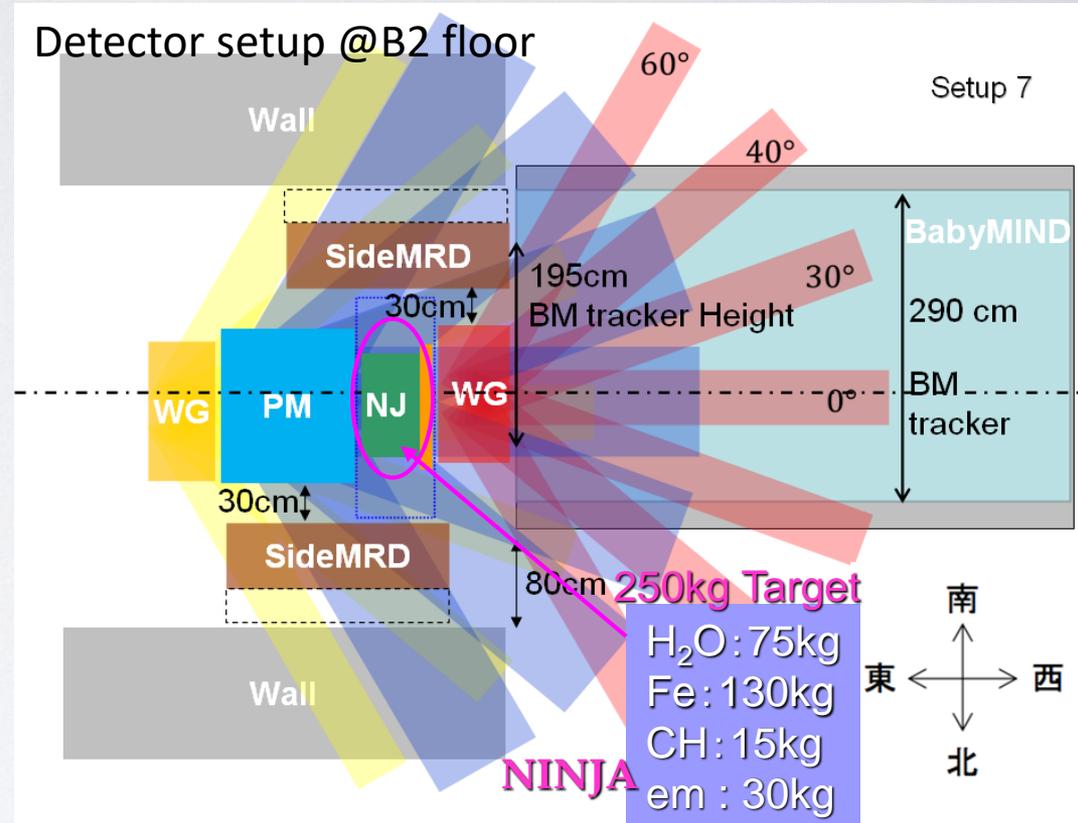
EMPHATIC

Experiment to <u>M</u>easure the <u>P</u>roduction of <u>H</u>adrons <u>A</u>t a <u>T</u>est beam <u>I</u>n <u>C</u>hicagoland

EMPHATIC Collaboration
~20 collaborators from Chiba, FNAL, ICRR, Kavli IPMU, KEK, Kobe, Kyoto, Nagoya, TRIUMP
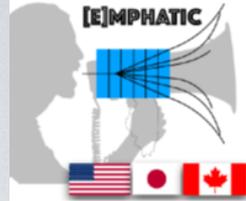
- Physics goals
  - Hadron production measurements for neutrino experiments (T2K, NOνA, MINERνA, HK, DUNE, NINJA, atmospheric neutrinos, …)
    - **Data with p_b < 15 GeV/c**
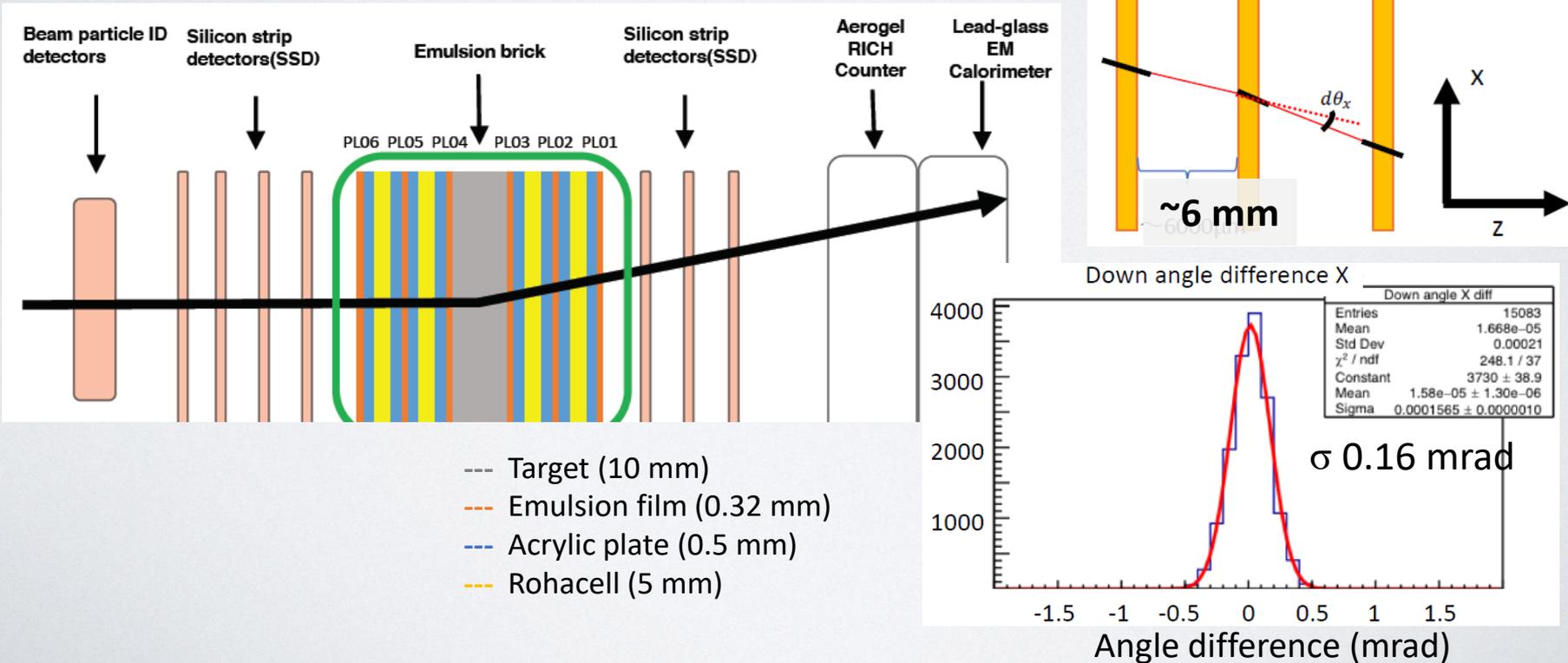   - **Precise measurement of forward scattering**

Target + SSD (**+emulsion**)
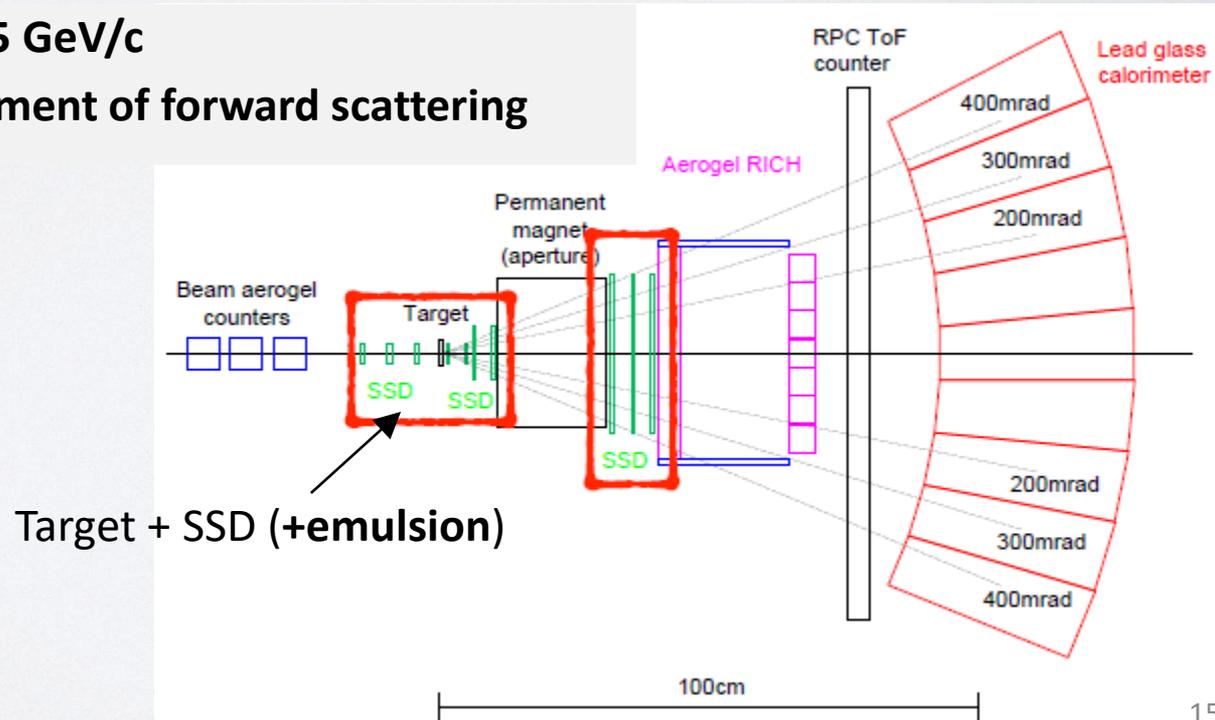
EMPHATIC data taking in 2018

- Beam momentum: 20, 30, 120 GeV/c

- Measurements with SSD (target: graphite, steel, aluminum)
- Measurements with emulsion (target: graphite)

Setup with a emulsion brick

Beam particle ID detectors
Silicon strip detectors(SSD)
Emulsion brick
Silicon strip detectors(SSD)
Aerogel RICH Counter
Lead-glass EM Calorimeter

PL06 PL05 PL04 PL03 PL02 PL01

--- Target (10 mm)
--- Emulsion film (0.32 mm)
--- Acrylic plate (0.5 mm)
--- Rohacell (5 mm)

PL03   PL02   PL01

$d\theta_x$

X

Z

~6 mm

Down angle difference X

Down angle X diff	
Entries	15083
Mean	1.668e−05
Std Dev	0.00021
χ^2 / ndf	248.1 / 37
Constant	3730 ± 38.9
Mean	1.58e−05 ± 1.30e−06
Sigma	0.0001565 ± 0.0000010

σ 0.16 mrad

Angle difference (mrad)

16

Timetable on the planned amount of emulsion films

Requirement for gel/film: work at 20°C for 4 months

Project	2019	2020	2021	2022	2023	…	2026 …
NINJA	**120 m²** 41k ν int.			**360 m²** 123k ν int.		**800 m²** 769k ν int.	(osci. νe 550)
EMPHATIC	**10 m²** 3×10^5 p+C	**104 m²** 10^6 p+C	**208 m²** 10^6 π+Al,Fe, K+C,Al,Fe				
SHiP			**100 m²**				**7000 m²** ~10k ντ, anti-ντ int.
DsTau			**560 m²** (2021-2022) 2×10^8 proton-tungsten int.				
FASERν			**625 m²** (2021-2023) 20k νμ, 1.3k νe, ~20 ντ int.				To be planned

Summary

- Several neutrino projects are progressing, employing state-of-the-art emulsion techniques

  - **NINJA**: Precise measurement of $\nu\mu$ and νe interactions
  - **EMPHATIC**: Precise measurement of hadron production
  - **SHiP**: Study of tau-neutrino interactions (~10000 $\nu\tau$ and anti-$\nu\tau$ interactions)
  - **DsTau**: Measurement of tau-neutrino production
  - **FASERν**: Study of TeV neutrinos from LHC

- The development through the B02 project will pave a way to realize future physics programs

Backup

# Cross section measurements in high energy
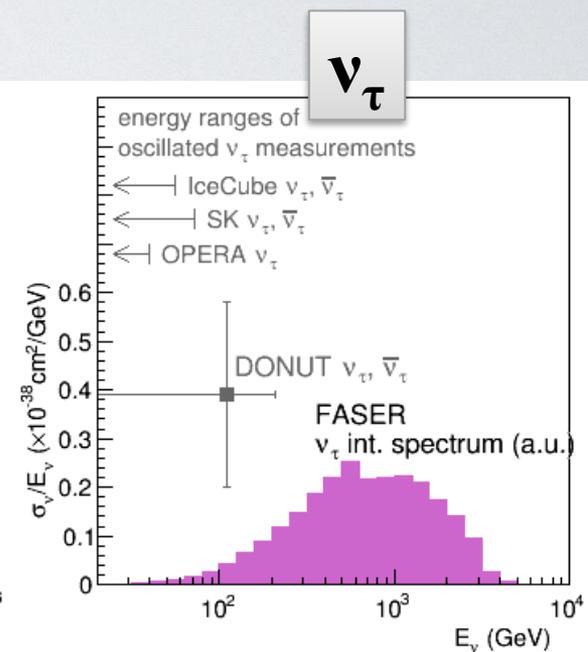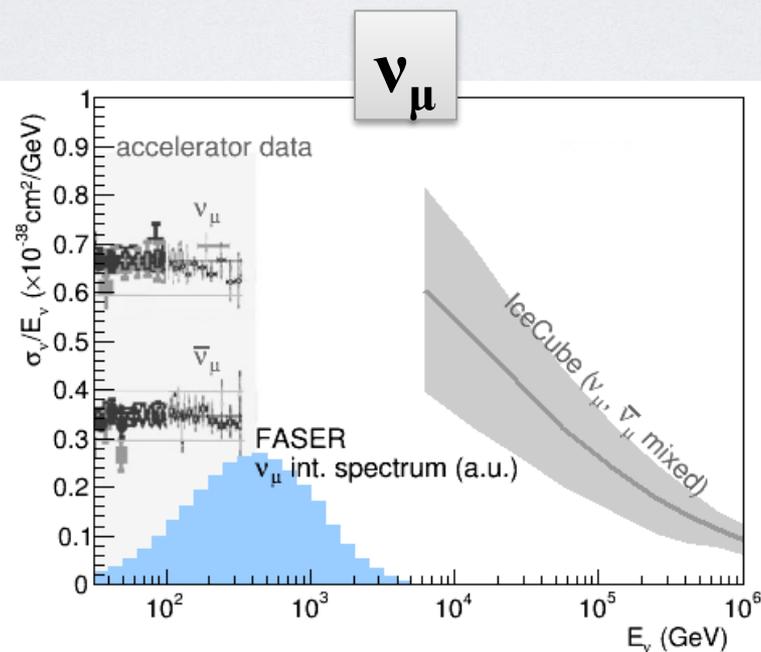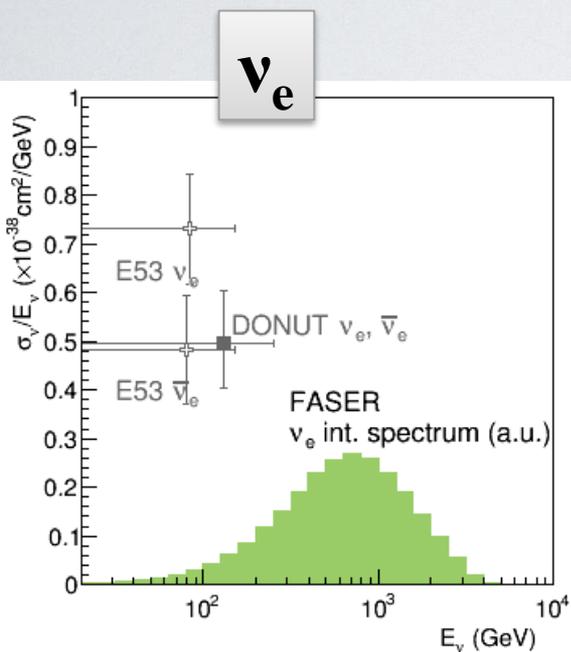
Motivation for high energy neutrinos

- Neutrino-quark scattering are basic tools to study interactions between leptons and quarks

  - Those in high energy (DIS regime) tell fundamental interactions between neutrinos and quarks

- Flavor physics with high energy neutrinos, ν_e, ν_μ, ν_τ and charm, beauty

- BSM search, e.g. flavor anomaly involving heavy leptons and quarks

Muon neutrino cross-sections (PDG)
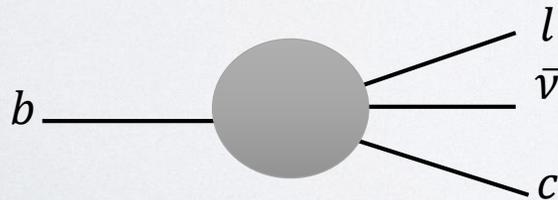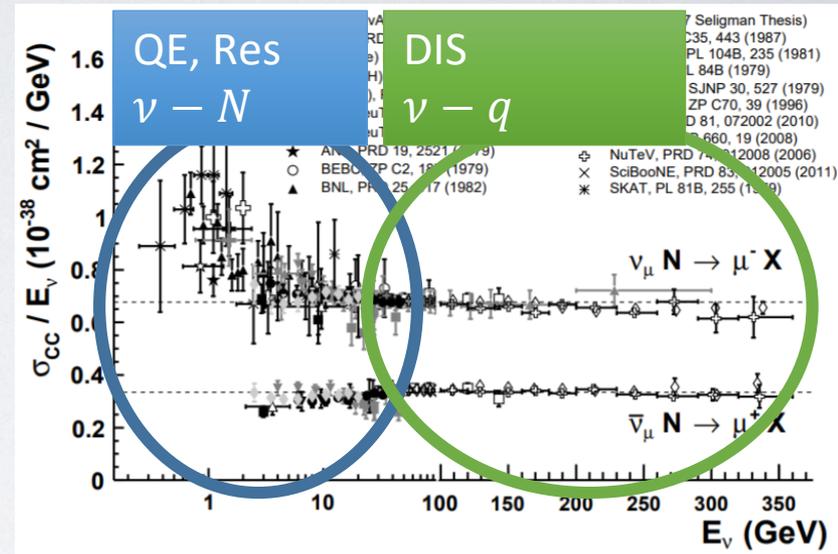
Anomalous b semi-leptonic decay

$\bar{\nu}N \to \ell \bar{B}X$

$\nu N \to \ell BDX$

ν CC b production
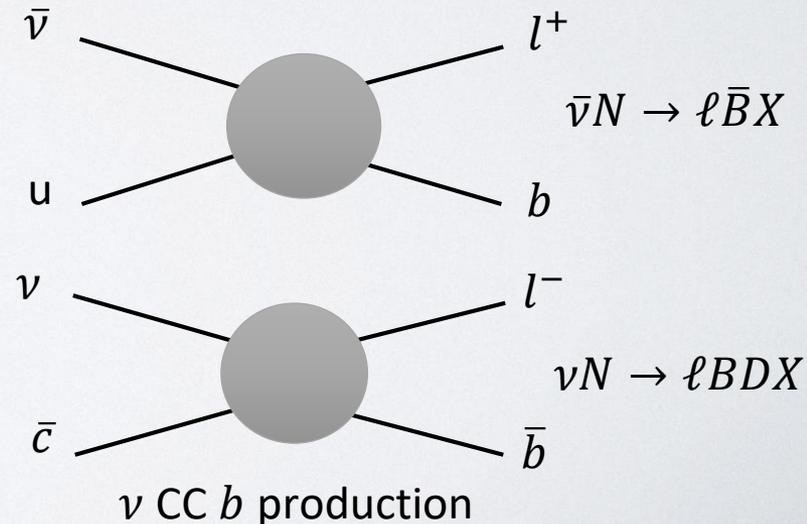
Inspired by B anomaly Lepton Universality with ν_τ

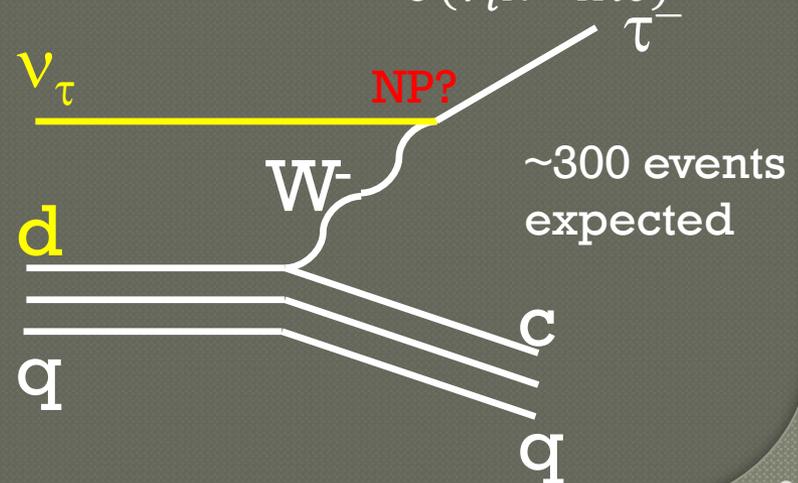- B anomaly is **a hint** for a violation of the lepton universality with **tau neutrino**.
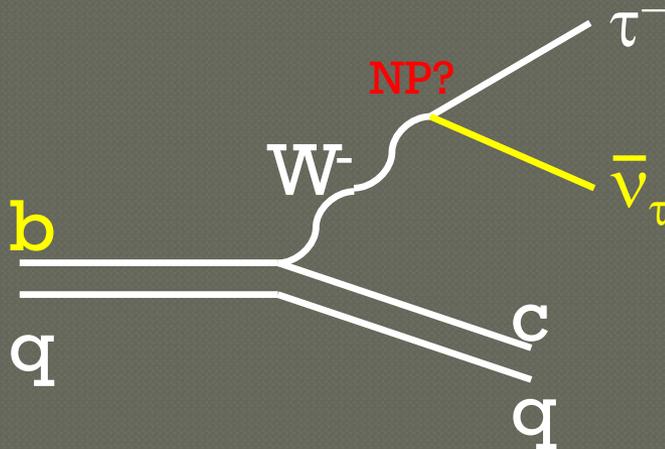
$$R(D) = \frac{\Gamma(B \to D\tau\nu)}{\Gamma(B \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(B \to D^*\tau\nu)}{\Gamma(B \to D^*\ell\nu)}$$

R(D) : 0.297±0.017(SM) vs 0.391±0.041±0.028(Exp.)
R(D*) : 0.252±0.003(SM) vs 0.322±0.018±0.012(Exp.)

Belle, BABAR, LHCb
4 sigma from SM
30% difference

- Approach from interaction $R(c) = \frac{\sigma(\nu_\tau N \to X\tau c)}{\sigma(\nu_l N \to Xlc)}$
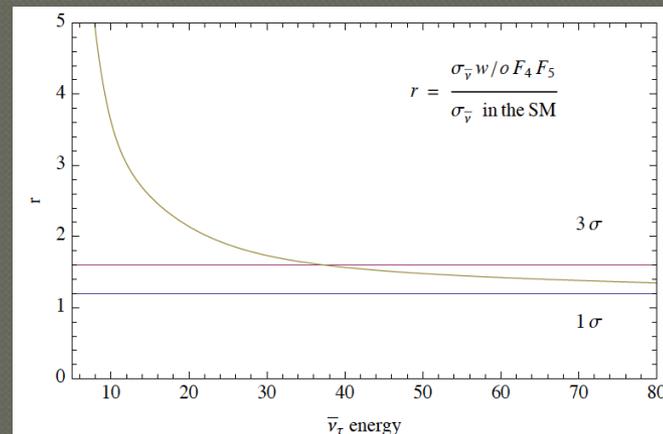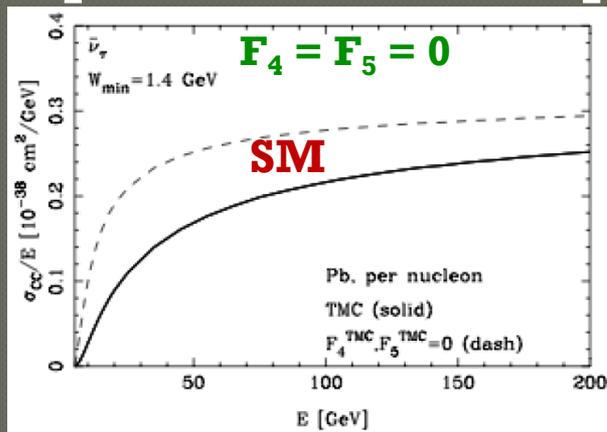
~300 events expected

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Structure function F_4 and F_5

- Structure function **only accessible by tau neutrino**

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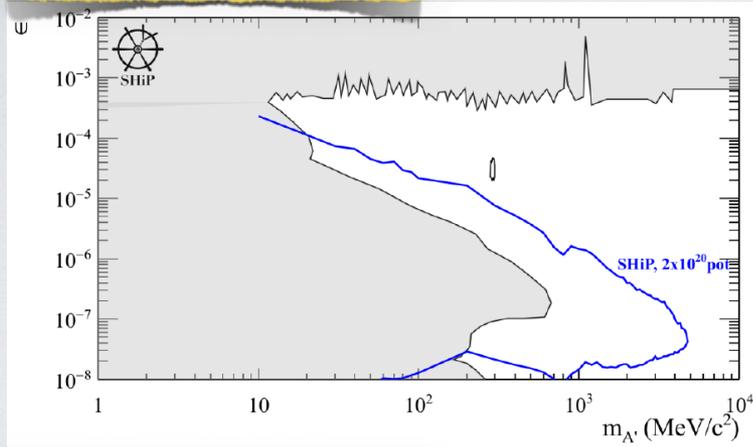
- Dependent on the lepton mass

$F_4 = F_5 = 0$

SM

$\bar{\nu}_\tau$
$W_{min} = 1.4$ GeV
Pb, per nucleon
TMC (solid)
$F_4^{TMC}, F_5^{TMC} = 0$ (dash)

σ_{CC}/E [10^{-38} cm^2/GeV]
E [GeV]

$r = \dfrac{\sigma_{\bar{\nu}} \, w/o \, F_4 F_5}{\sigma_{\bar{\nu}} \, \text{in the SM}}$

3σ

1σ

r
$\bar{\nu}_\tau$ energy

At LO $F_4 = 0$, $2xF_5 = F_2$

Hidden Sector Sensitivities   based on 2x10²⁰ pot @400 GeV in 5 years
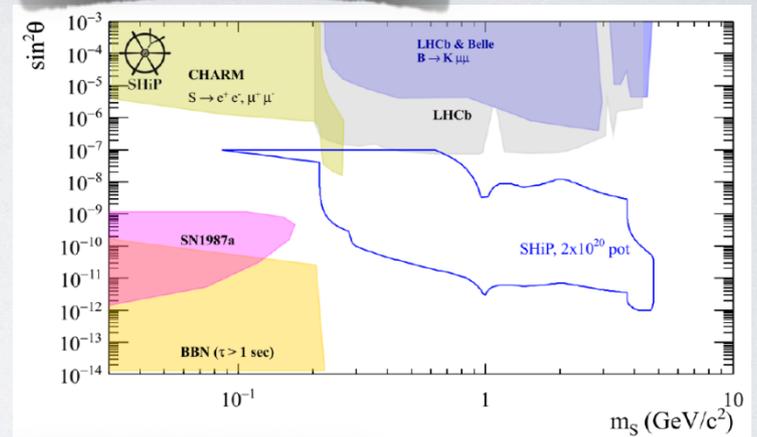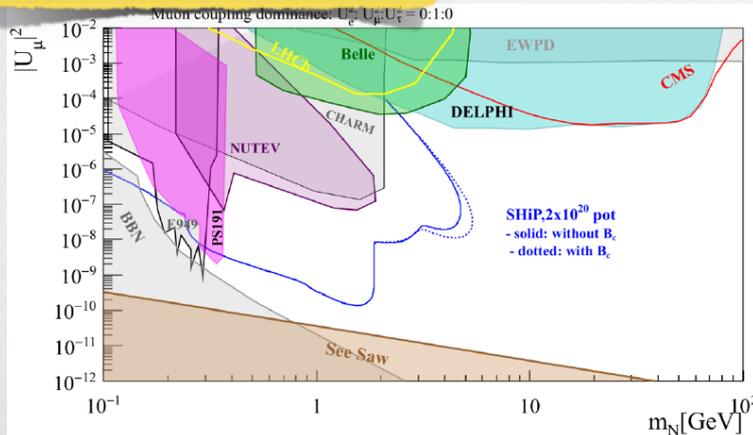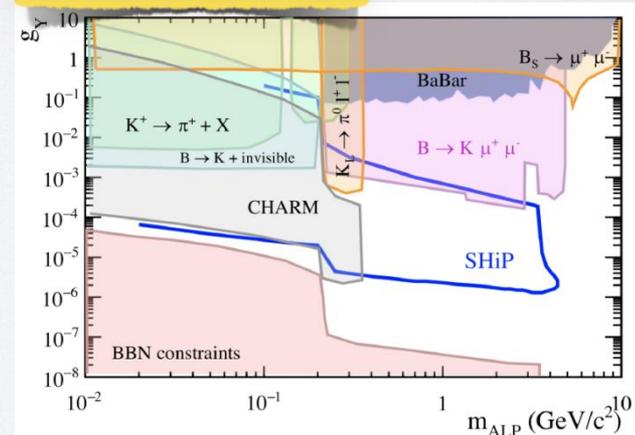
SK

Atmospheric

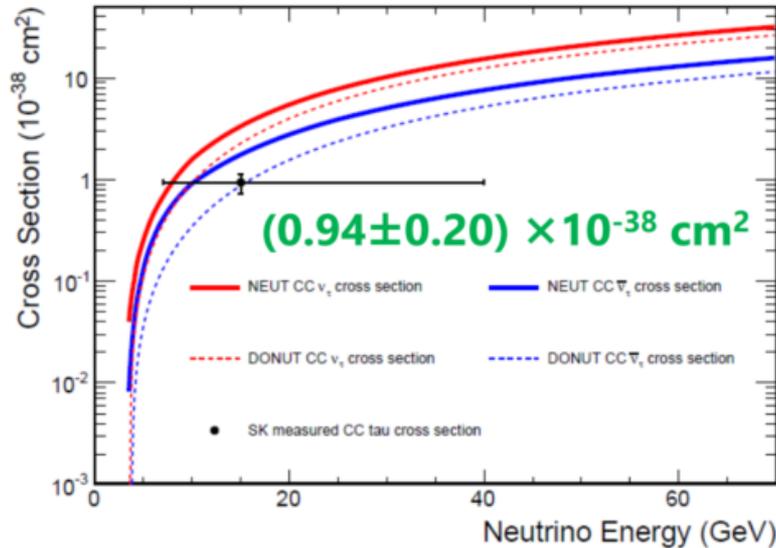$$\nu_\mu \rightarrow \nu_\tau \ \& \ \overline{\nu_\mu} \rightarrow \overline{\nu_\tau}$$

$\sigma_{meas} = (1.47 \pm 0.32) \ \sigma_{theory}$

$(0.94 \pm 0.20) \times 10^{-38} \ cm^2$

OPERA
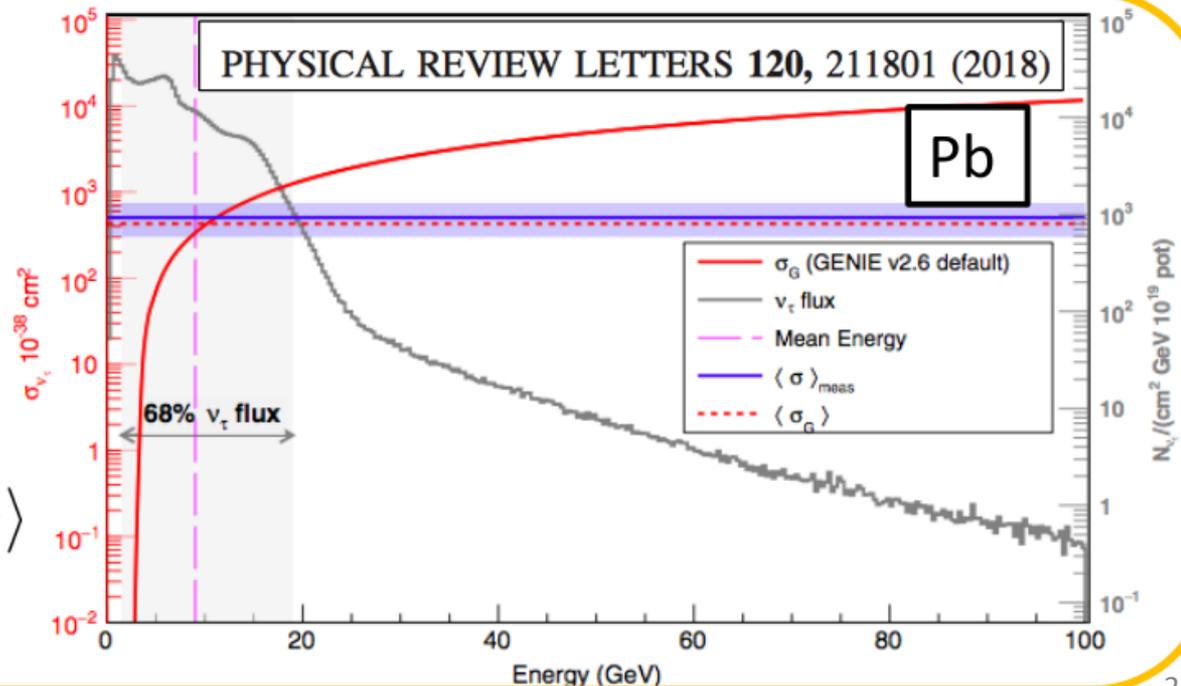
CNGS ν_μ beam

$$\nu_\mu \rightarrow \nu_\tau$$

σ with a Pb nucleus

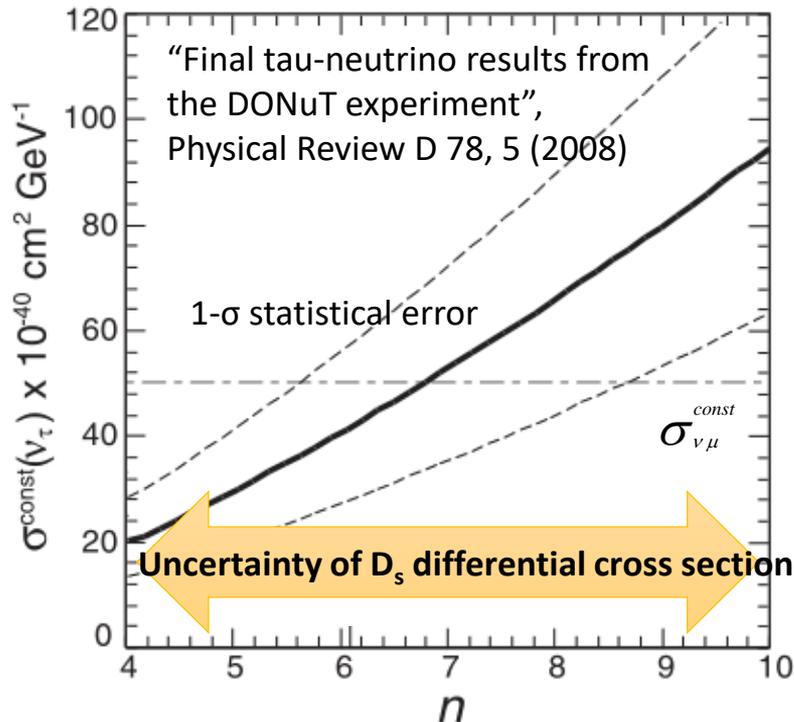$\langle\sigma\rangle_{meas} = (5.1^{+2.4}_{-2.0}) \times 10^{-36} \ cm^2$

$$\langle\sigma\rangle_{meas} = (1.2^{+0.6}_{-0.5}) \ \langle\sigma_G\rangle$$

PHYSICAL REVIEW LETTERS **120**, 211801 (2018)

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Systematic uncertainty in the DONuT measurement

9 ν_τ CC events observed with an estimated background of 1.5 events

Parameter-dependent cross section result

"Final tau-neutrino results from the DONuT experiment", Physical Review D 78, 5 (2008)

1-σ statistical error

$\sigma_{\nu\mu}^{const}$

Uncertainty of D_s differential cross section

ν_τ CC cross section $\qquad \sigma_{\nu\tau}(E) = \sigma_{\nu\tau}^{const} \times E_{\nu\tau} \times K_\tau(E)$

The largest uncertainty in DONuT:
D_s differential cross section (used to calculate the ν_τ flux)

Parametrization used in DONUT

$$\frac{d^2\sigma}{dx_F \, dp_T^2} \propto (1 - |x_F|)^n \exp(-bp_T^2)$$

longitudinal dependence   transverse dependence

No experimental result effectively constraining the D_s differential cross section

The energy-independent part was parameterized as

$$\sigma_{\nu\tau}^{const} = 7.5(0.335 n^{1.52}) \times 10^{-40} \, cm^2 GeV^{-1}$$

To reduce the systematic uncertainty in the ν_τ CC cross-section **lower than 10%**, the parameter *n* has to be determined at **a precision of ~0.4**

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Charm production cross section results

$$\frac{d^2\sigma}{dx_F dp_T^2} \propto (1-|x_F|)^n \exp(-bp_T^2)$$

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	-	$n(D^0, D^+) = 7.5 \pm 3.2$
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		$n(D) = 8.6 \pm 2.0$ $b(D) = 0.8 \pm 0.2$
E781 (SELEX)	Σ^- (sdd) / 600					~350 D_s^- events, ~130 D_s^+ events ($x_F > 0.15$) $n(D_s^-) = 4.1 \pm 0.3$ (leading effect) $n(D_s^+) = 7.4 \pm 1.0$
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 ($D^\pm, D^0, D_s^\pm$) $n(D^\pm, D^0, D_s^\pm) = 6.1 \pm 0.7$ $b(D^\pm, D^0, D_s^\pm) = 1.08 \pm 0.09$
E769	$\pi^\pm$ / 250	2.1 ± 0.4		9 ± 1		1665 ± 54 events ($D^\pm, D^0, D_s^\pm$) $n(D^\pm, D^0, D_s^\pm) = 4.03 \pm 0.18$ $b(D^\pm, D^0, D_s^\pm) = 1.08 \pm 0.05$
NA32	π / 230	1.5 ± 0.5		7 ± 1		

(Results from LHCb at √s = 7, 8 or 13 TeV are not included since the energies differ too much)

No experimental result effectively constraining the D_s differential cross section at the desired level or consequently the ν_τ production
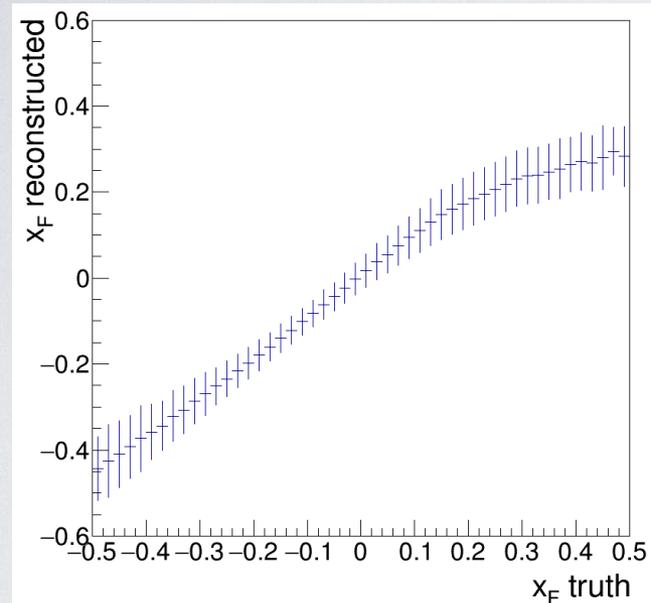
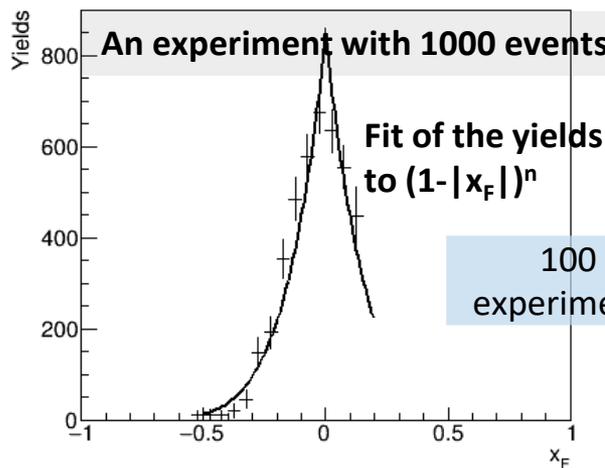# Precision of D_s differential cross-section measurement

Parametrization used in DONUT

$$\frac{d^2\sigma}{dx_F dp_T^2} \propto (1-|x_F|)^n \exp(-bp_T^2)$$

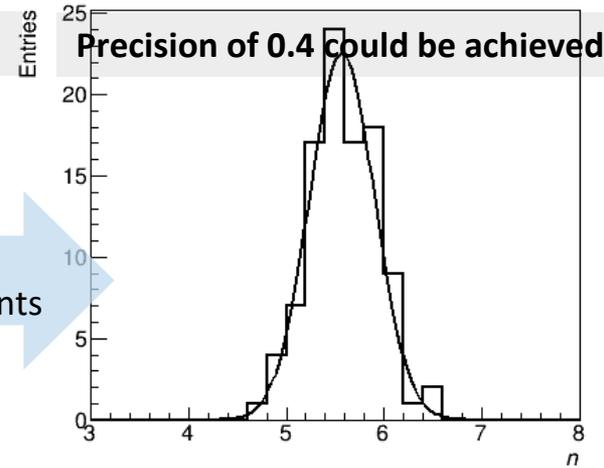longitudinal dependence   transverse dependence

x_F is a longitudinal profile of D_s:

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

Reconstructed x_F
(corrected by the efficiency)

Estimated parameter n

An experiment with 1000 events

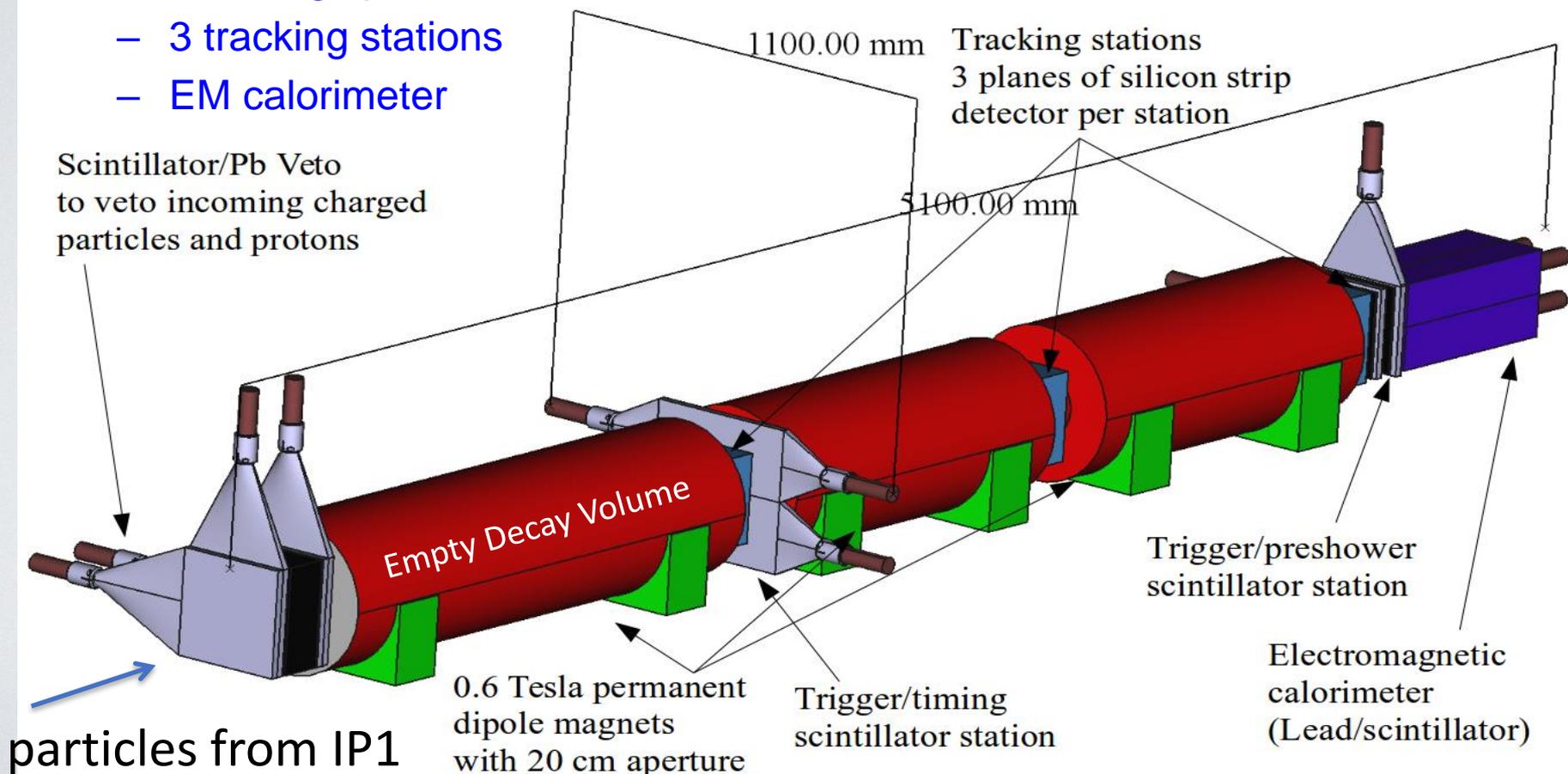Fit of the yields to $(1-|x_F|)^n$

100 experiments

Precision of 0.4 could be achieved

- The parametrization currently used is not so good → A more appropriate parametrization will be investigated for future measurement
- A precision of 0.4 could be achieved using 1000 events (→ $\Delta\sigma/\sigma \sim 10\%$)
- The central value of the n distribution is systematically shifted due to smearing of the Ds momentum
  → Unfolding of the reconstructed x_F distribution is to be applied (method will be investigated)

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THE FASER DETECTOR

- The entire detector is 5.5 m long. It consists of
    - Scintillator veto
    - 1.5 m-long decay volume
    - 2 m-long spectrometer
    - 3 tracking stations
    - EM calorimeter

Scintillator/Pb Veto
to veto incoming charged
particles and protons

1100.00 mm

Tracking stations
3 planes of silicon strip
detector per station

5100.00 mm

Empty Decay Volume

0.6 Tesla permanent
dipole magnets
with 20 cm aperture

Trigger/timing
scintillator station

Trigger/preshower
scintillator station

Electromagnetic
calorimeter
(Lead/scintillator)

particles from IP1

DARK PHOTON SENSITIVITY REACH

- Combine $\pi, \eta \to A'\gamma$, $qq \to qqA'$, etc., plot $N_S = 3$ (10 makes little difference)

- FASER: R=10cm, L=1.5m, Run 3;   FASER 2: R=1m, L=5m, HL-LHC
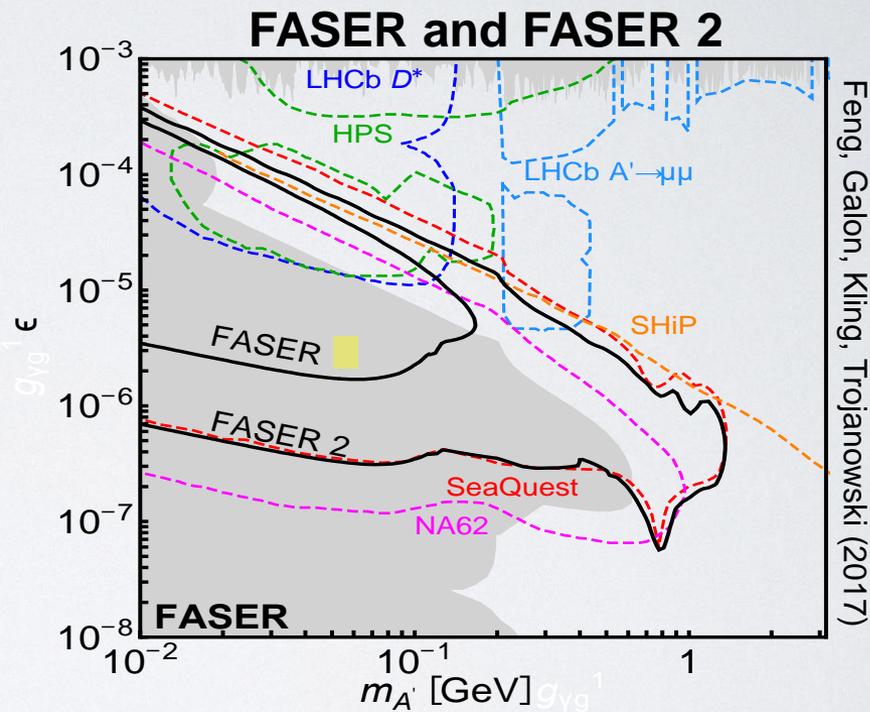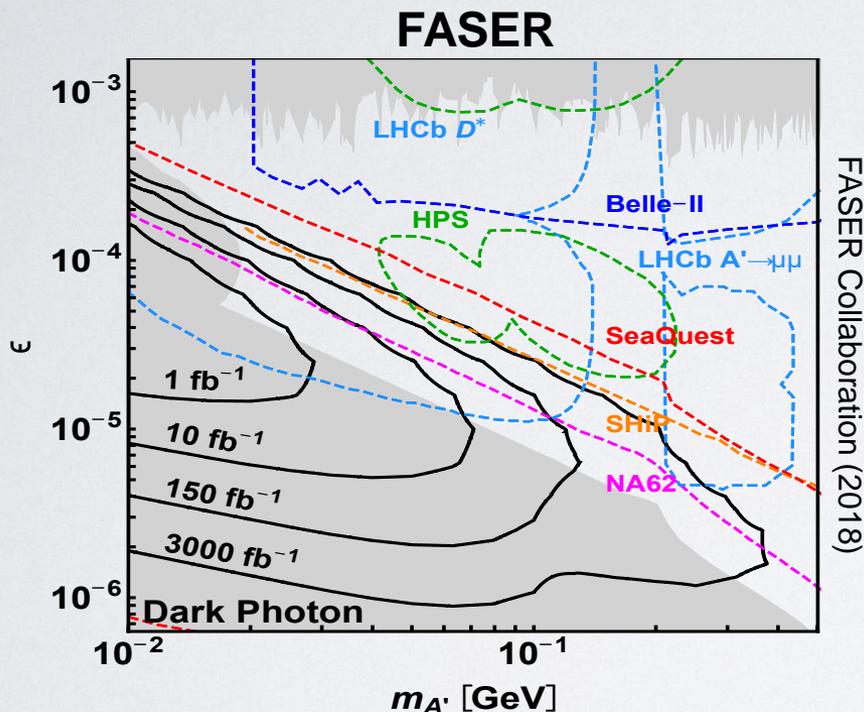
- FASER probes new parameter space with just 1 fb^{-1} starting in 2021

- Without upgrade, HL-LHC extends (L*Volume) by factor of 3000; with possible upgrade to FASER 2, HL-LHC extends (L*Volume) by ~10^6

MORE FASER PHYSICS: ALPS WITH PHOTONS

- FASER can also discover ALPs and other LLPs produced not at the IP, but further downstream

- For example: ~TeV photon from IP collides with TA(X)N ~140 m downstream (between beams), creates Axion-Like Particle, which decays through a $\rightarrow \gamma\gamma$, detected in FASER calorimeters

- "Photon beam dump" or "light shining through walls"