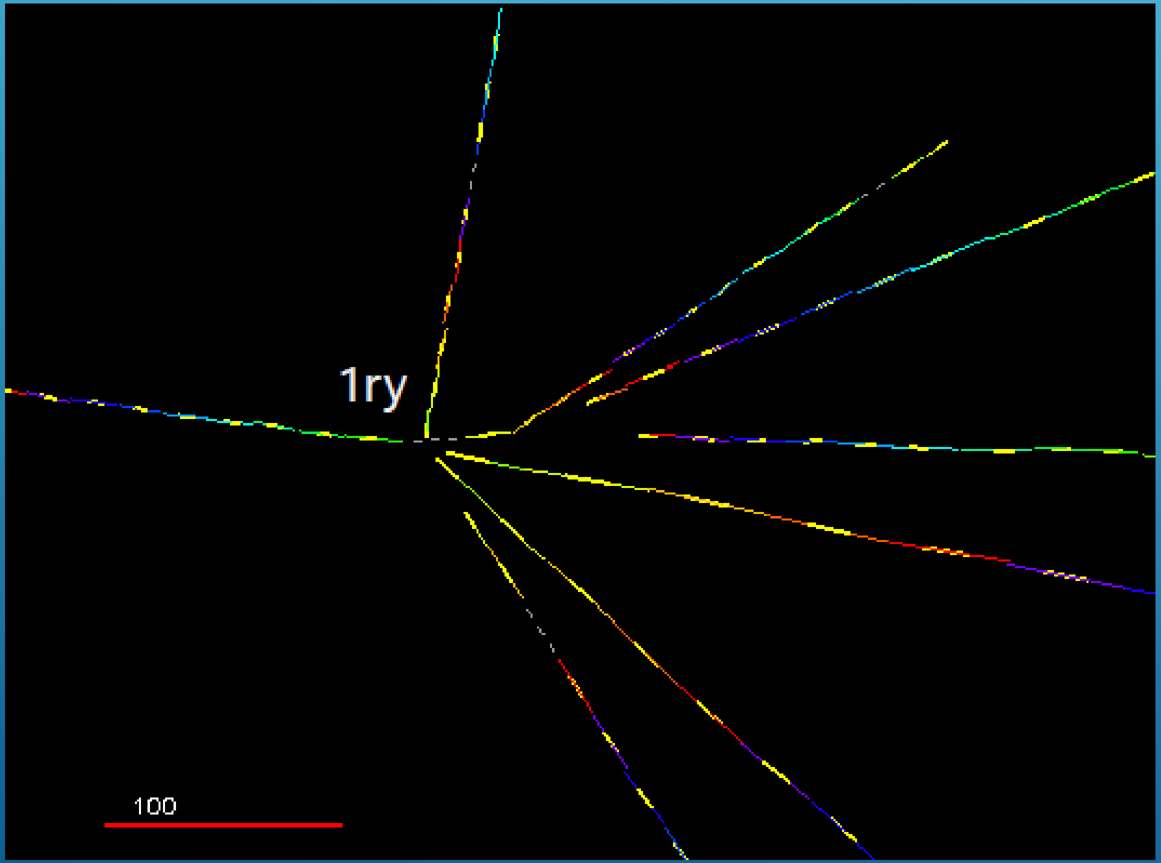
DsTau (NA65) Experiment: Study of Tau Neutrino Production at CERN/SPS

Elena FIRU

on behalf of the DsTau (NA65) Collaboration

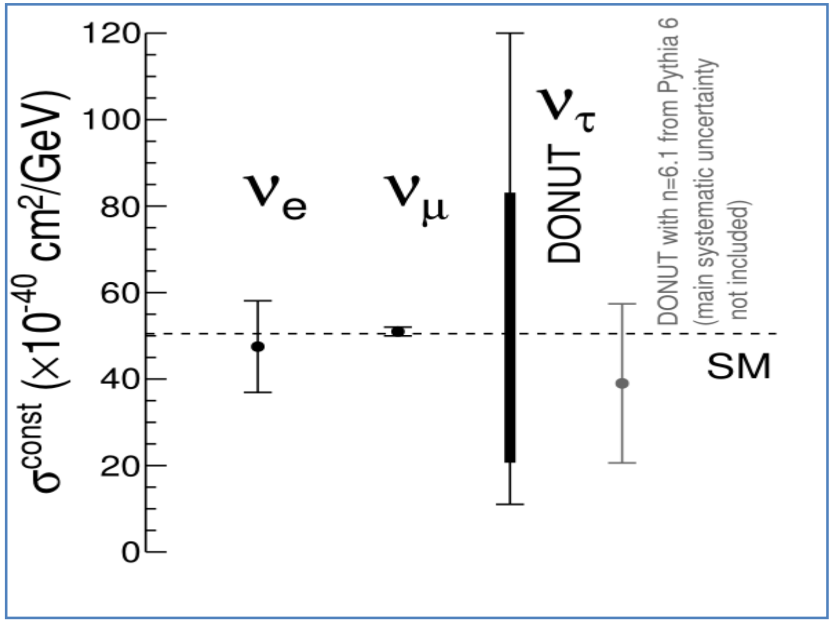


Institute of Space Science, Bucharest, Romania

Study of tau neutrinos

✓ **Tau neutrino is one of the least studied particles**

- only a few measurements:
  - Direct ν_τ beam: **DONUT** (DIS) - first direct evidence of tau-neutrino interaction
  - Oscillated ν_τ: **OPERA** (DIS), **Super-K** (QE), **IceCube** (DIS).
- cross section error >50% (DIS) due to systematic uncertainty in ν_τ production



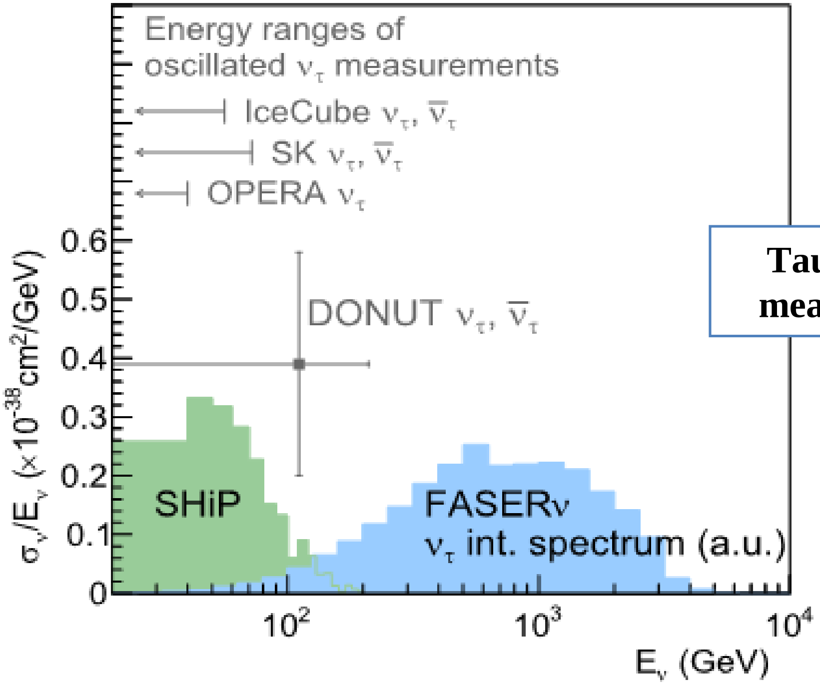
Cross section measurements of the three neutrino flavors (in high-energy region)

✓ **A new precise measurement of the ν_τ cross section**

- test lepton universality
- new physics effects in ν_τ CC interactions

✓ **Future ν_τ measurements**

- SHiP (SPSC-P-350): high statistics measurement at the SPS
- reduce statistical uncertainty from 33% in DONuT
- indirectly FASER



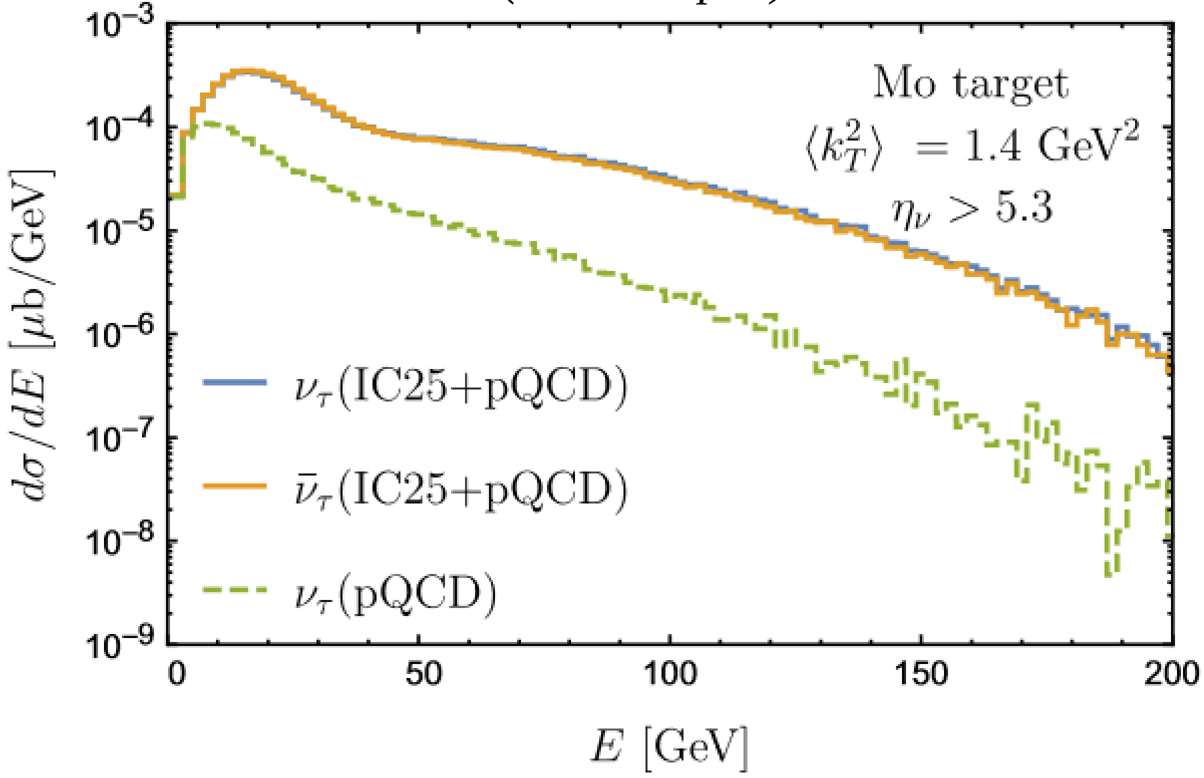
Tau-neutrino measurements

✓ **The intrinsic charm parameterization predicts an enhancement of forward charm production**

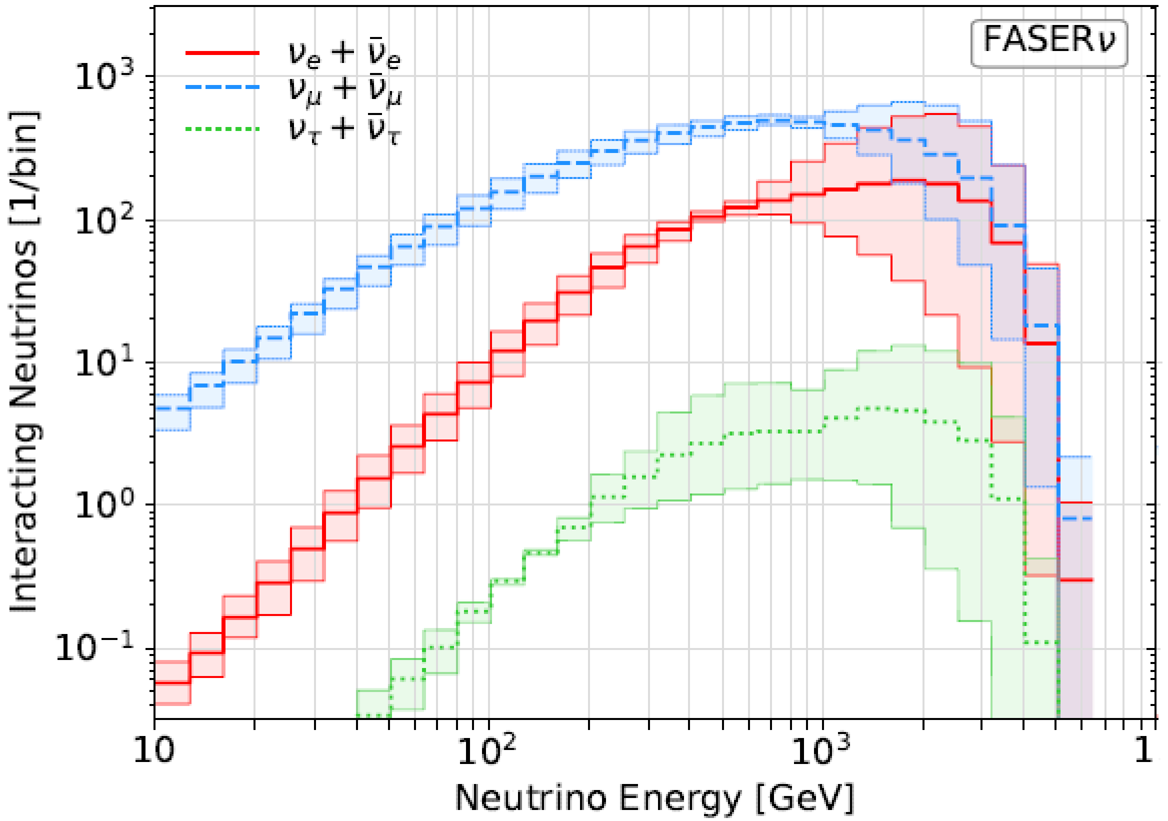
- May change forward neutrino rate
- Could be a key input for high energy neutrino measurements by large scale Cherenkov observatories such as IceCube

✓ **Neutrino experiments need data on the forward charm production**

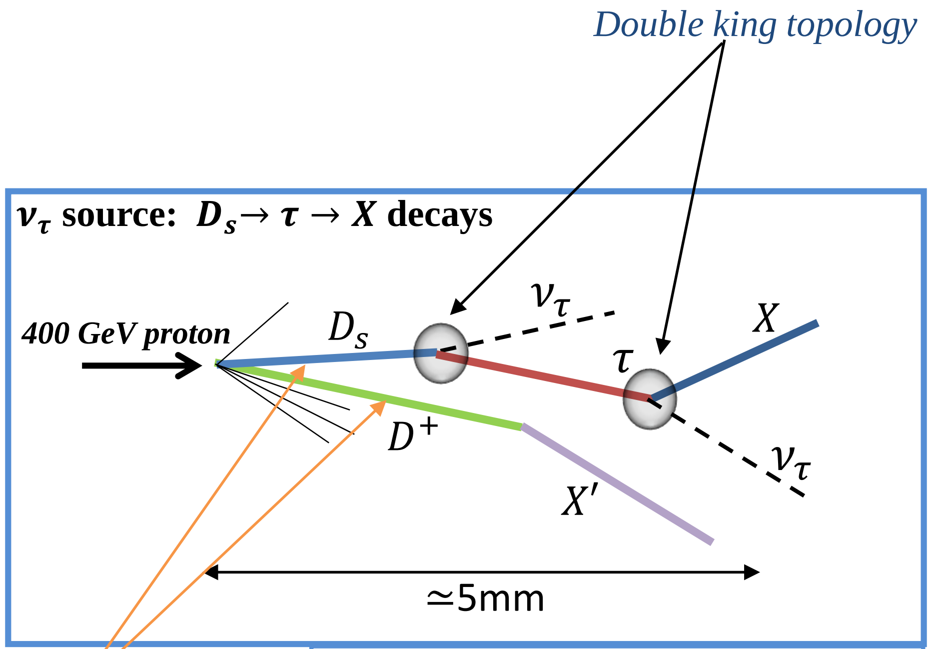
SHiP case (400 GeV p-N) interaction



FASER case (7 - 7 TeV)



The DsTau (NA65) experiment – physics goals



Double charm hadron production

ν_τ production study: DsTau (NA65)

- **DsTau goals**
  - Study of the tau neutrino production by **D_s** decays
  - reduce the systematic uncertainty of ν_τ flux production from *50% to 10 %*
  - first measurement of D_s double differential production cross section
  - fundamental input for future ν_τ experiment *(like FASER, SHiP)*

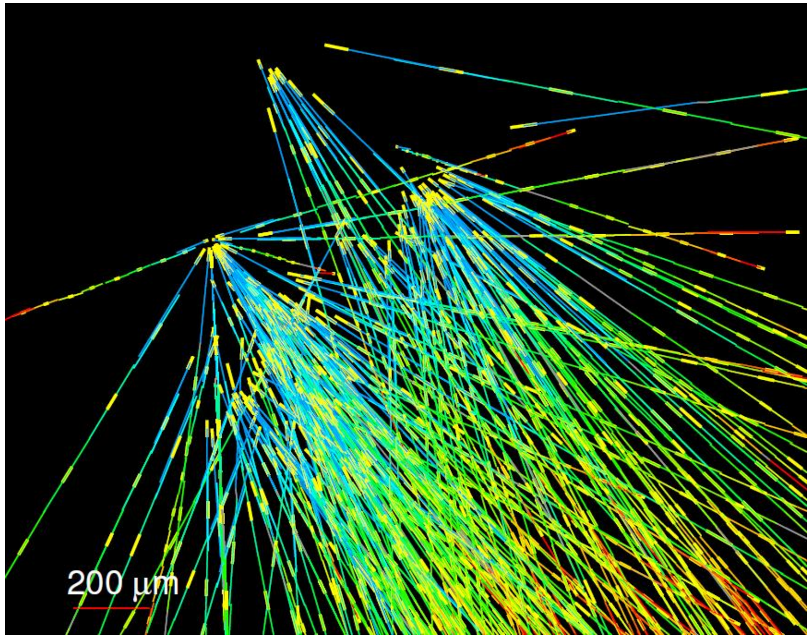
- **By product: Study of open charm production**
  - In tungsten/molybdenum target: ~ 4.5 x 10^5 charm pairs produced
  - In other materials (emulsion/plastic): ~ 2.7 x 10^5 charm pairs produced
  - Detection of ~10^5 charm pairs

- **Principle of the experiment:**
  - detection of ”**double-kink + charm decay**” topology within few mm
  - 4.6×10^9 protons, 2.3×10^8 proton interactions in tungsten/molybdenum

1000 ⟶ $D_s \rightarrow \tau \rightarrow X$ *decays*

DsTau (NA65) @ CERN

- DsTau is an experiment of **SPS Research Programme** with the title “Study of tau neutrino production”
- It was approved as NA65 experiment in June 2019
- Detectors: modules of Nuclear Emulsions interlaid with tungsten/molybdenum, plastic in first part, and lead/tungsten plates, plastic in the second part
- Milestones:



Test beam 2016
- Test of detector structure

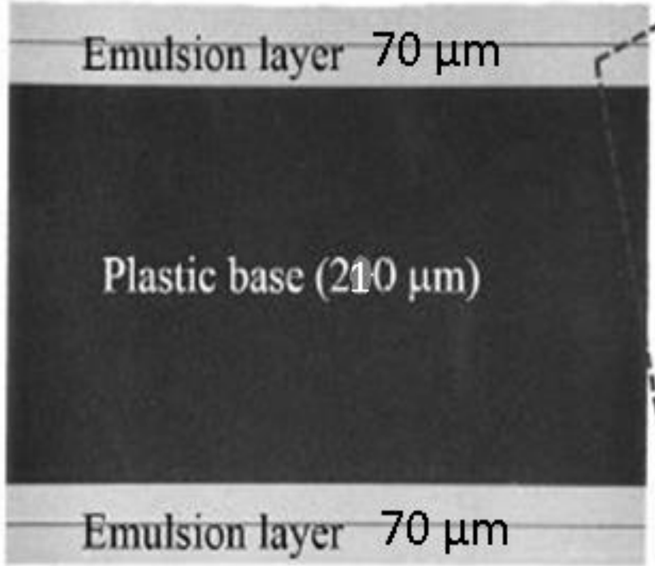
Test beam 2017
- Improved detector structure
- Refine exposure scheme

Pilot run 2018
- 1/10 of the full-scale experiment with tungsten target
- 30 modules, 50 m^2

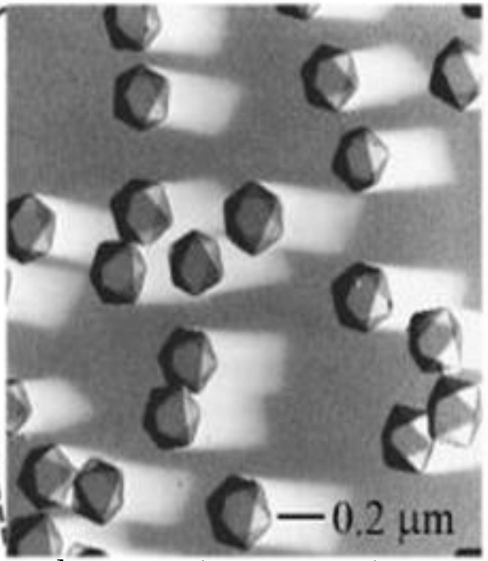
Physics run 2021-2022
- Full scale experiment with tungsten and molybdenum targets
- Aiming at 1000 $D_s \rightarrow \tau \rightarrow X$ events
- 10 % uncertainty on ν_τ flux

Nuclear emulsion detector

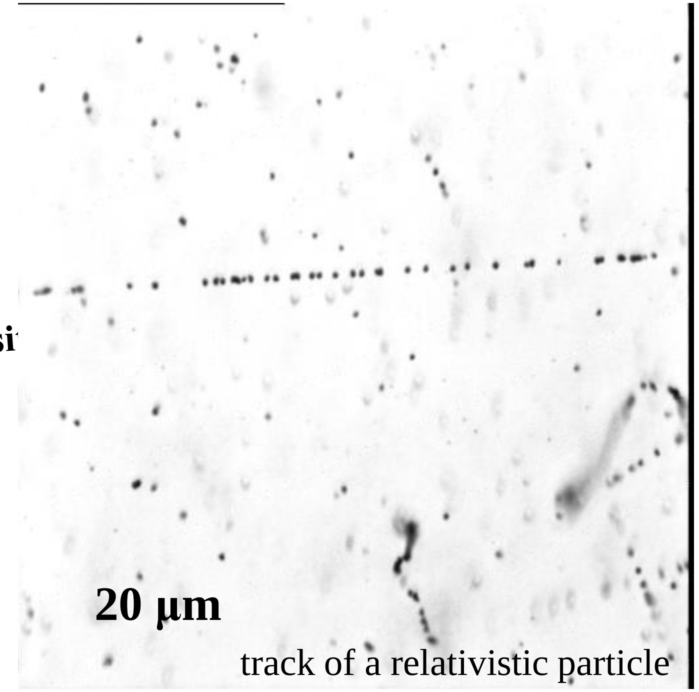
Emulsion films



cross-sectional view of an emulsion film



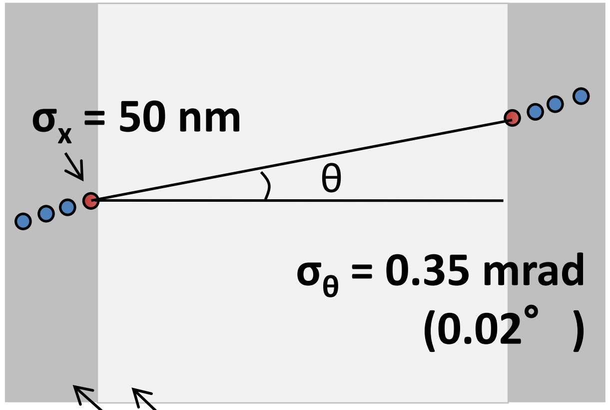
electron microscope picture of silver halide crystals



track of a relativistic particle

Single emulsion film

High angular resolution tracker

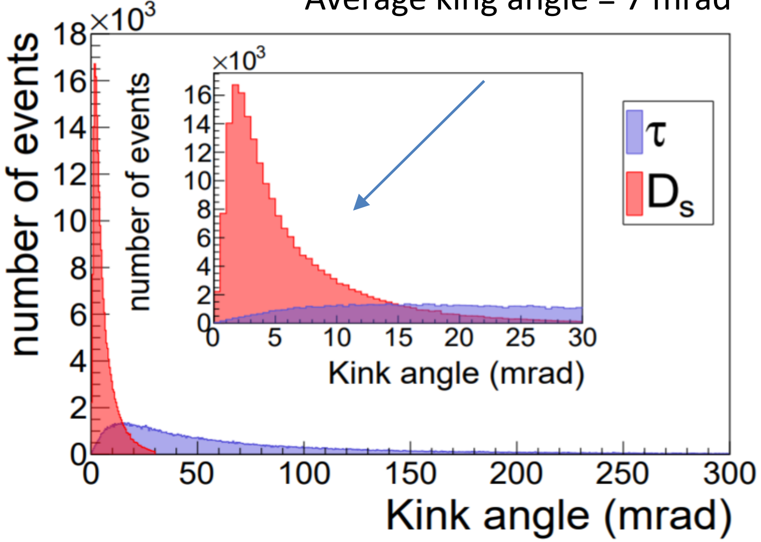


Plastic base (210 µm)

Emulsion layer (70 µm)

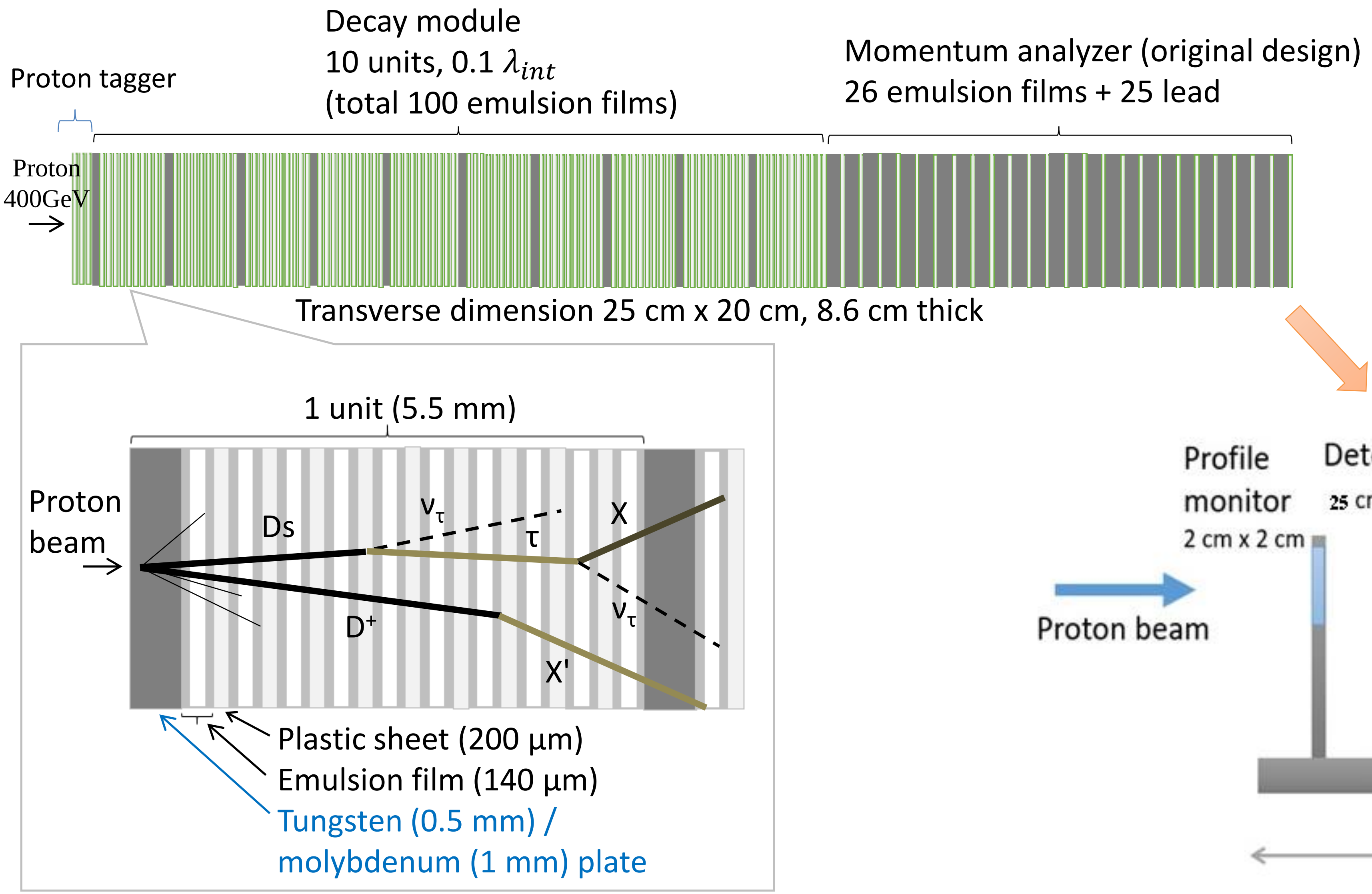
Kink angle of $D_s \rightarrow \tau$ decays

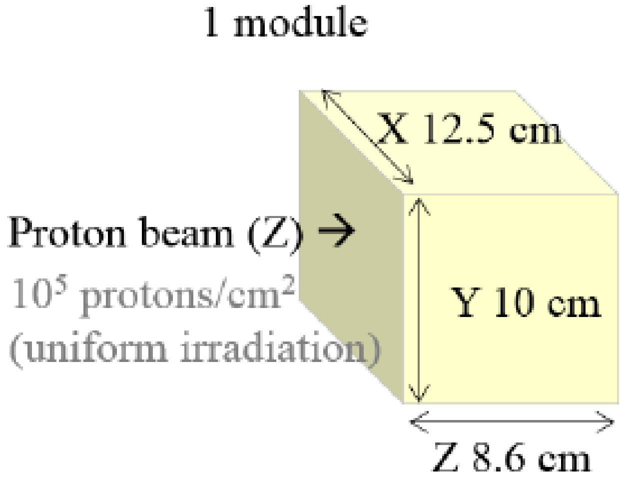
Average king angle = 7 mrad

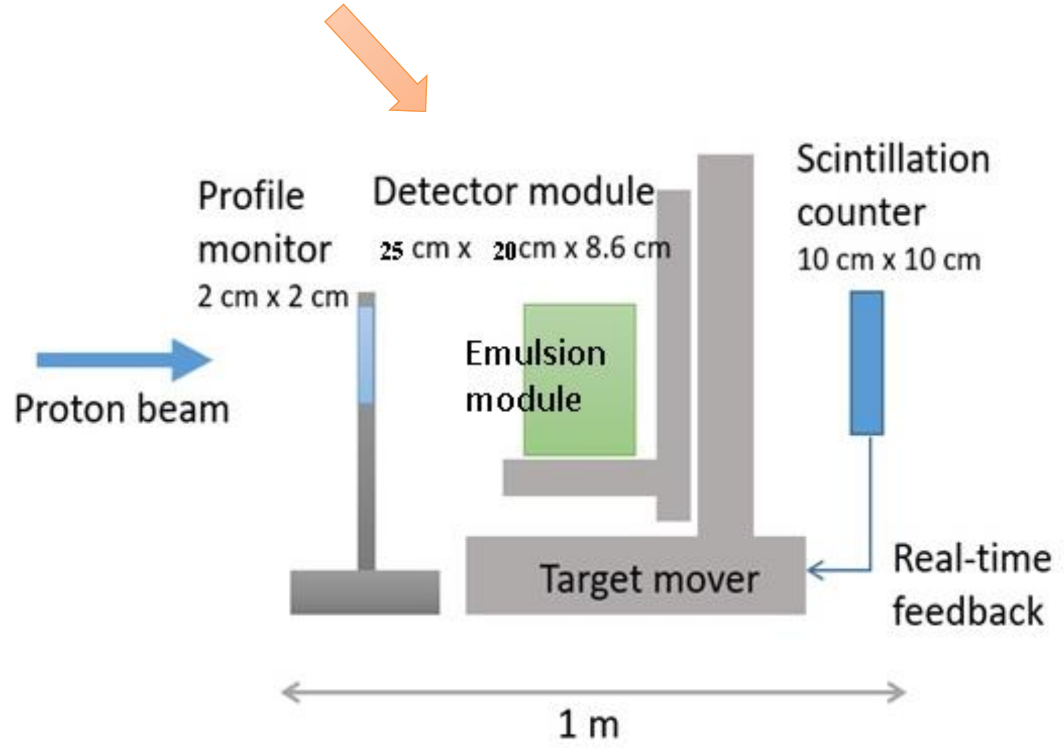


Experimental set-up (2016, 2017, 2018)

Emulsion based detector structure for $D_s \to \tau \to X$ measurement

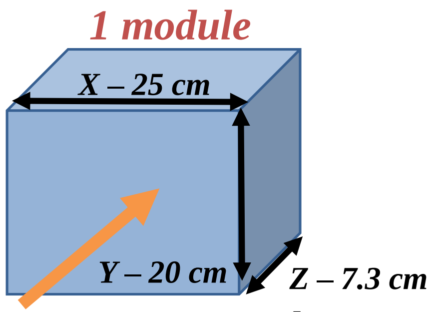






Experimental set-up

Module structure for momentum estimation was change for 2021 physics run



Proton beam (Z) - 10^5 protons/cm^2 (uniform irradiation)

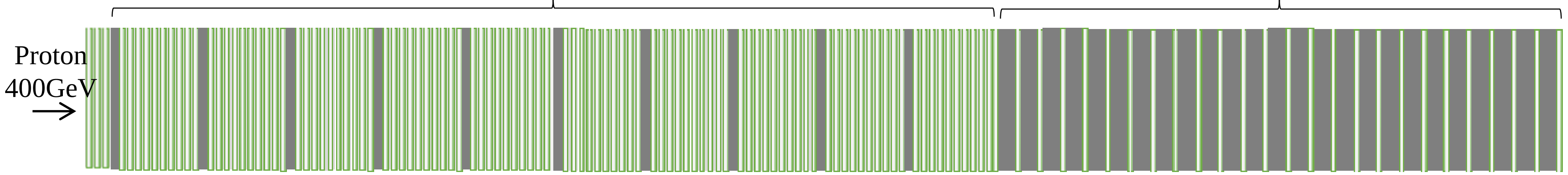
- ✓ **Momentum measurement is relevant to reject low energy events (MCS mimicking $D_s \to \tau \to X$ events)**

- **Initial structure had more material → too high track density**
  - **Dedicated scanning is required**
- **Reduce material, but still sufficient performance**
- **Making data taking procedure simple**

Initial

10 units (total 100 emulsion films)

ECC for momentum measurement (26 emulsion films interleaved with 1 mm thick lead plates)

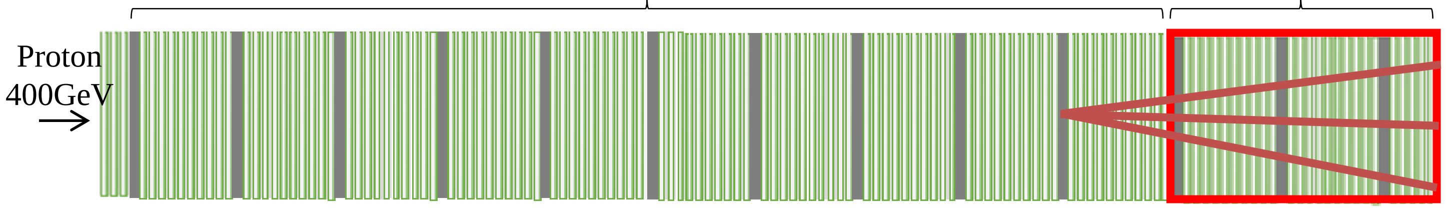


Starting with 2021

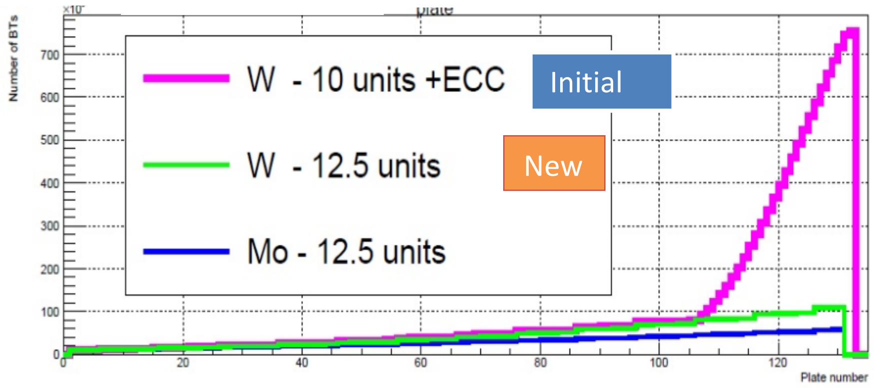
10 units (total 100 emulsion films)

Momentum analyzer for events at downmost tungsten plates:

3 tungsten plates and 25 emulsion plates



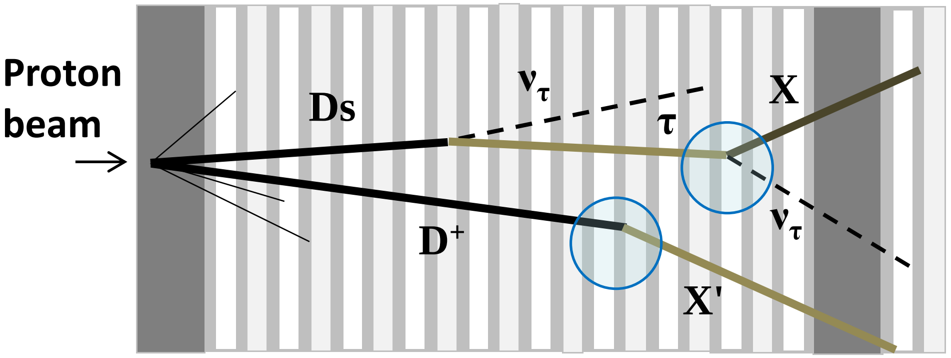
	Initial: lead emulsion ECC	*New:* additional tungsten units
Structure	25 – 1 mm lead, 26 emulsion plates	3 – 0.5 mm tungsten, 25 emulsion plates
Momentum resolution	15 – 40 % (upstream ev.) 35 – 45 % (downstream ev.)	15 – 40 % (upstream ev.) 35 – 45 % (downstream ev.)
Weight	15.0 kg	2.4 kg



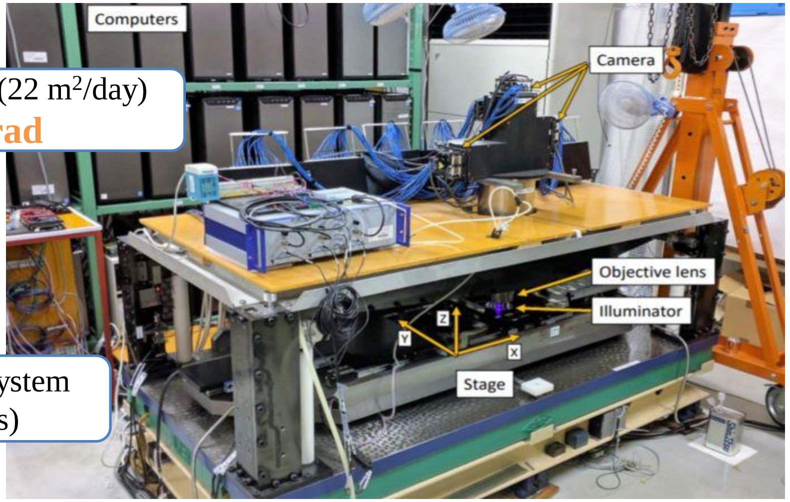
Data acquisition

Step 1

- Full area scanning by a fast scanning system to select $\tau \rightarrow X$
- It selects decays with $\Delta\theta > 100$ mrad



Hyper Track Selector (HTS)



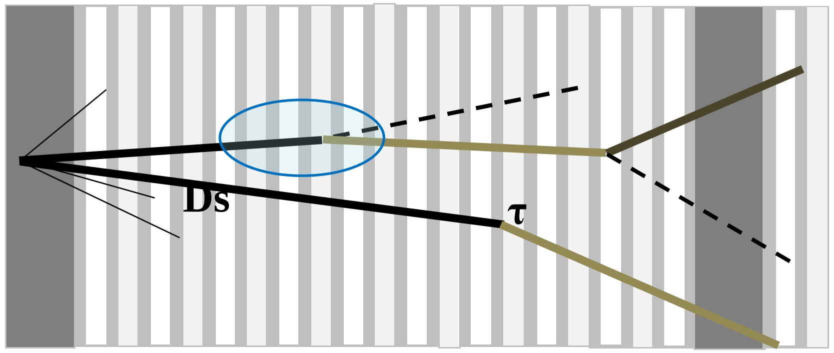
Scanning speed 0.5 m^2/h/layer (22 m^2/day)

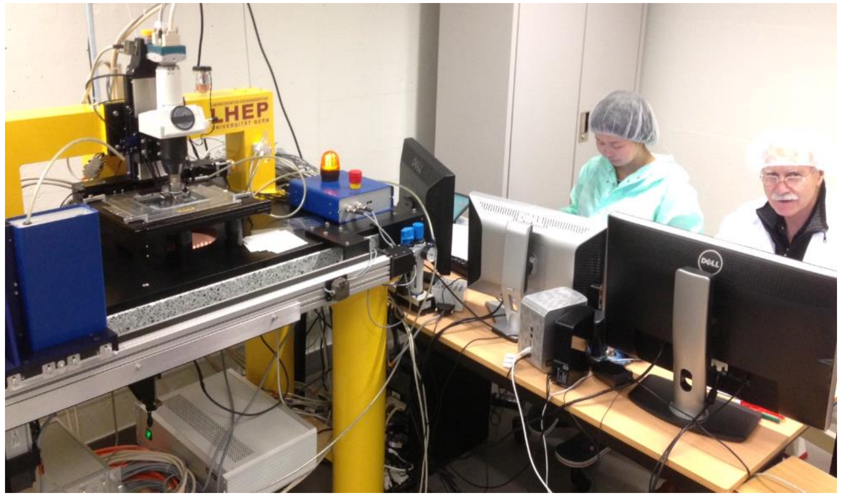
Angular resolution ~2 mrad

100x faster than the scanning system of OPERA (throughput 36 GB/s)

Step 2

- Precision measurement to detect $D_s \rightarrow \tau$ decay (a few mrad)
- Dedicated high-precision systems

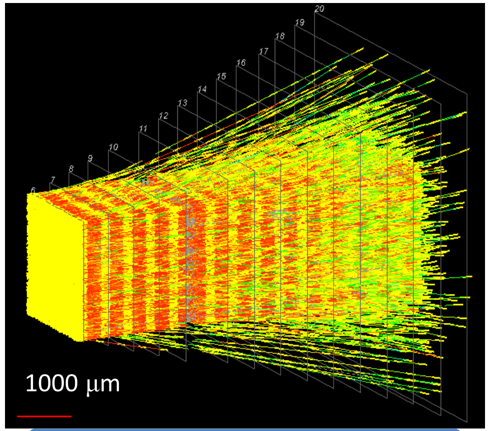




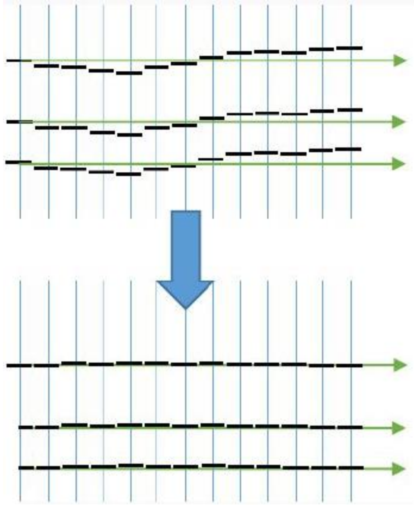
Angular resolution ~0.3 mrad

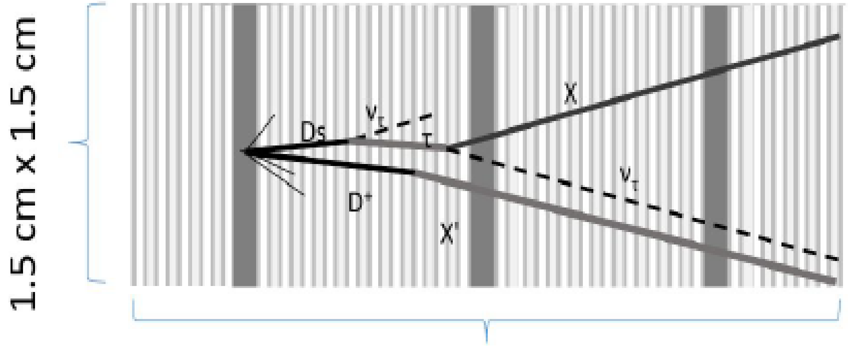
Alignment and track reconstruction

- ✓ alignment algorithm - very precise - sub micron
- ✓ track reconstruction - positions and angular correspondences
- ✓ average efficiency is higher than 95%.
- ✓ proton beam tracks were checked in detail
- ✓ processing in subvolues 1.5 cm x 1.5 cm x 30 plates



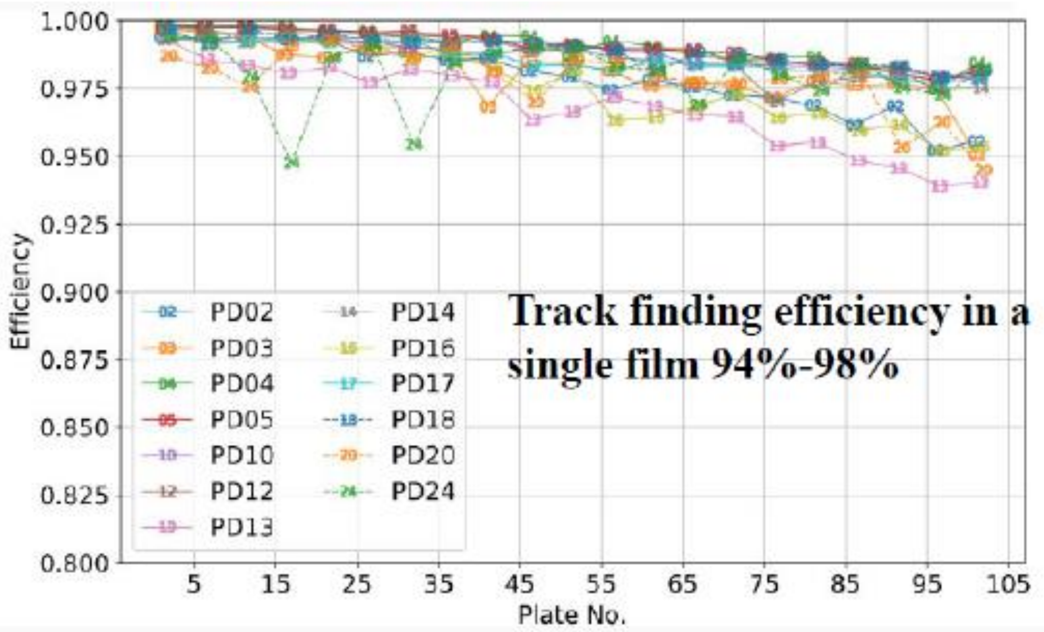
~4000 tracks in 2 x 2 mm^2, 15 films



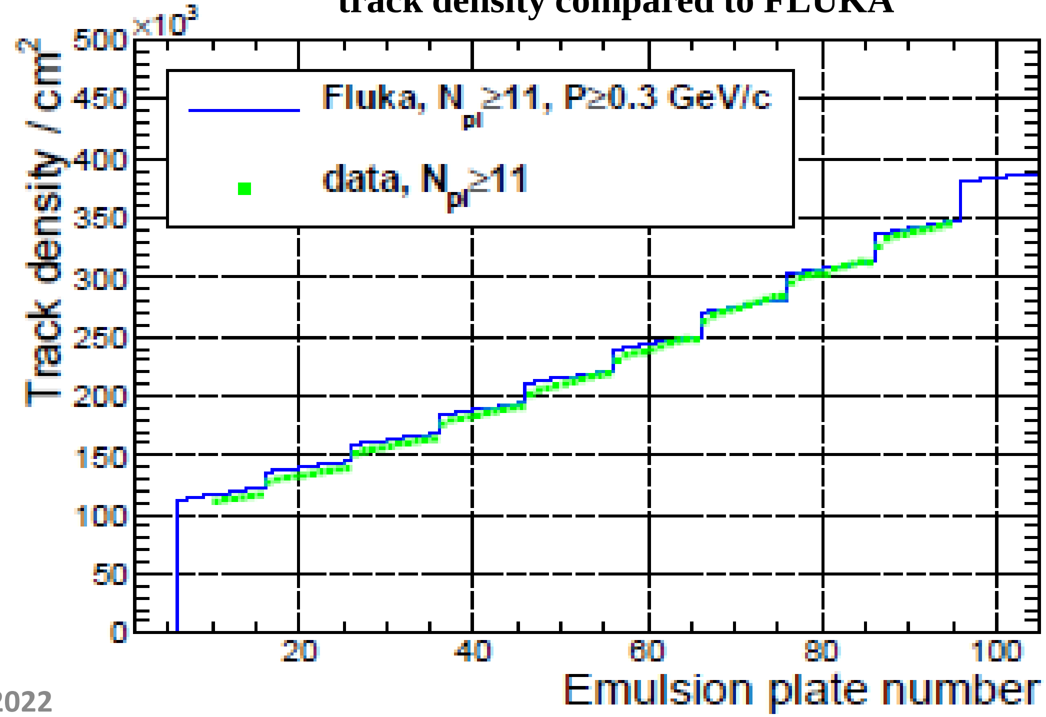


30 films

(two tungsten plates to reject low momentum daughter candidates)

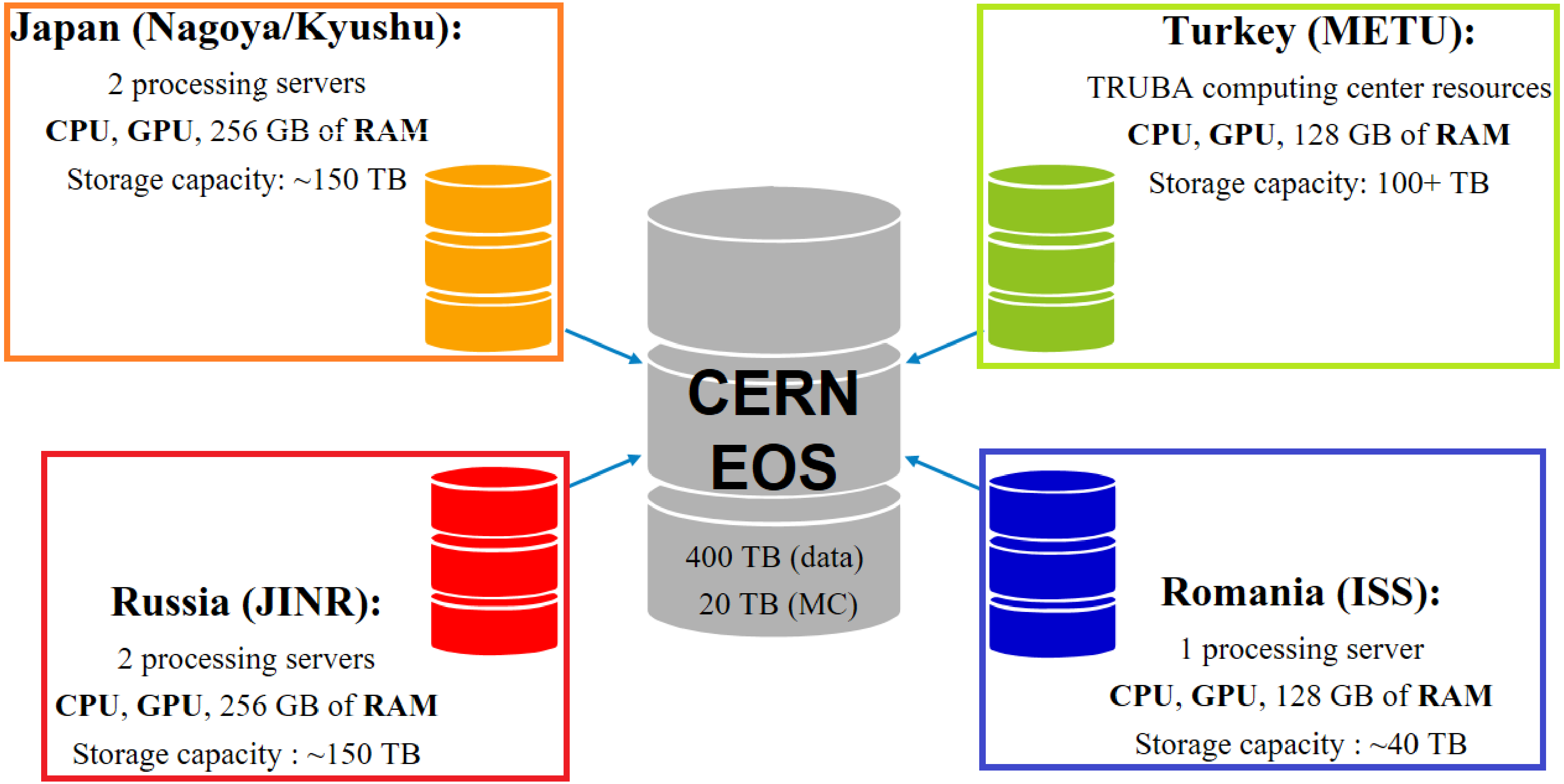


track density compared to FLUKA



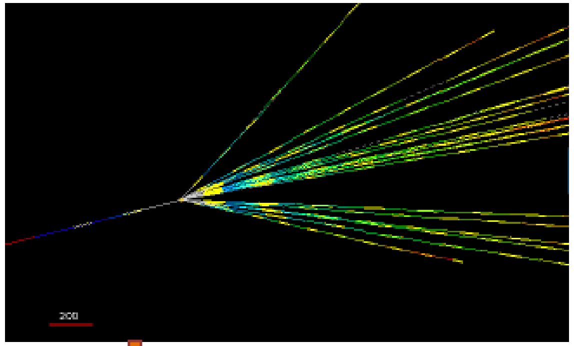
Alignment and track reconstruction

- ✓ film to film alignment and track reconstruction procedures require powerful processing servers with large memory **(~128 256 GB of RAM)** and disk space **(~5-10 TB for each data module**) resources
- ✓ up to now **25 out of 30 modules** for **2018 pilot run** have been fully processed (track reconstruction)
- ✓ the batch system of the **CERN computing** center is also going to be used to process the **next physics runs data**

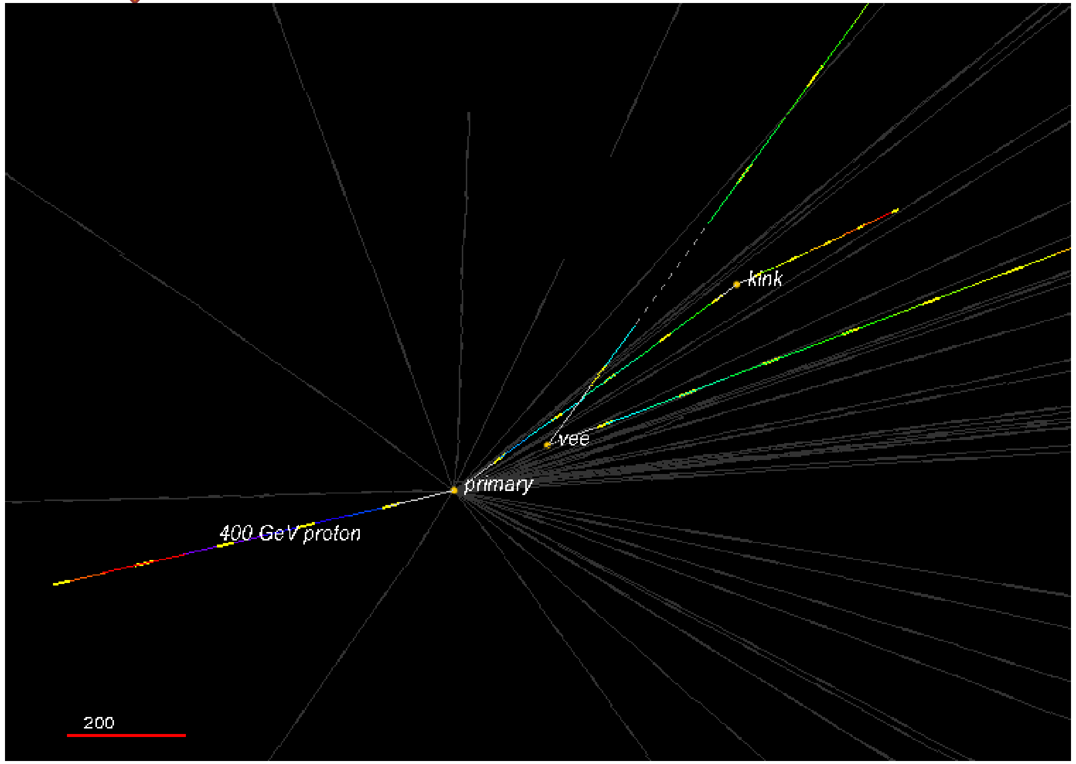


Vertex reconstruction

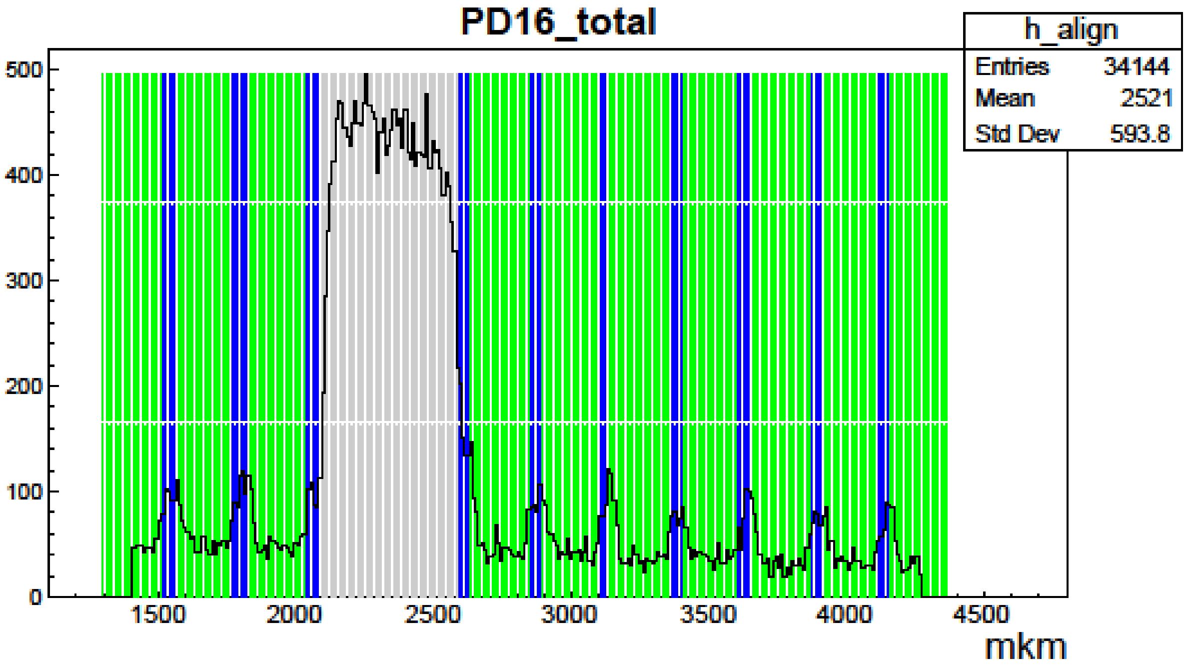
A double charm candidate event
with a neutral 2 prong (vee) and a charged 1 prong (kink) topology



- ✓ **Kink**
- IP of daughter 291.6 μm
- FL 2536.6 μm
- Kink angle 118 mrad
- ✓ **Vee**
- IP of daughters 20.9, 109.7 μm
- FL 554.5 μm
- Opening angle 242 mrad



Reconstructed vertex position in tungsten

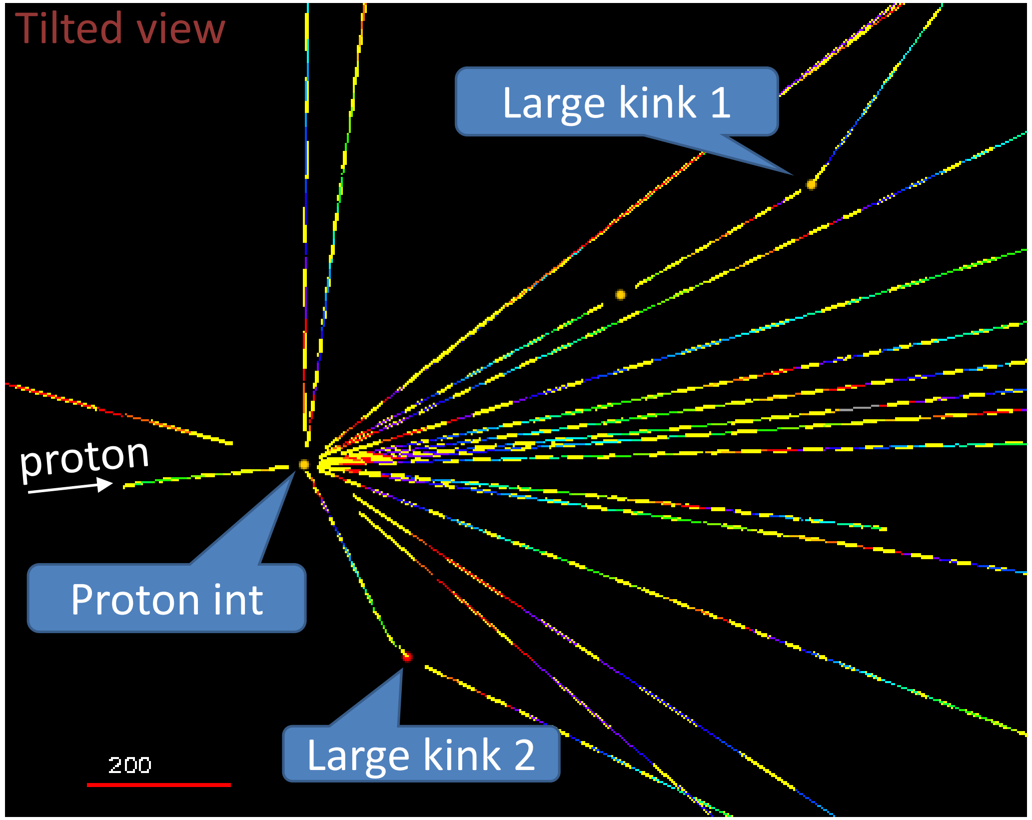


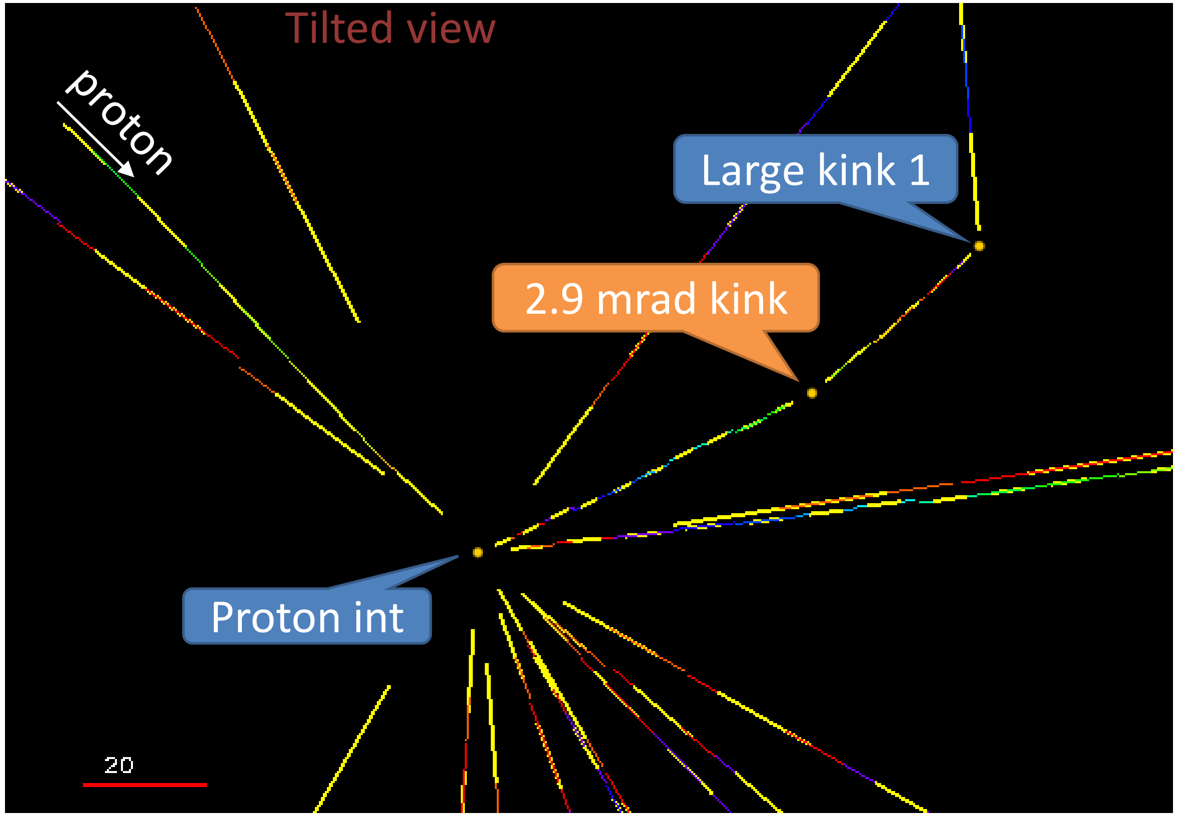
- ✓ fine detector structure is observed by reconstructed vertices
- ✓ *the results will be summarized into a paper soon*

Search for $D_s \rightarrow \tau$ events from 2018 pilot run

✓ $D_s \rightarrow \tau$ decay has a small kink angle ~ 7 mrad.

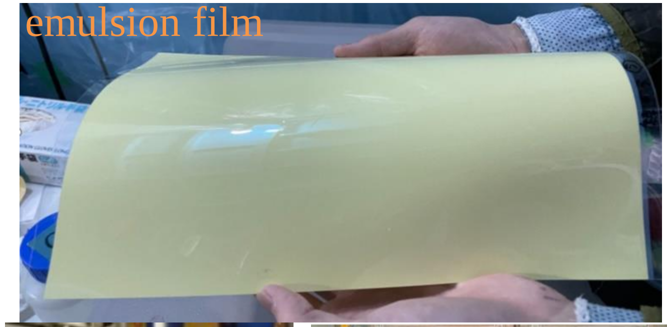
✓ An automated search of small kinks has been implemented





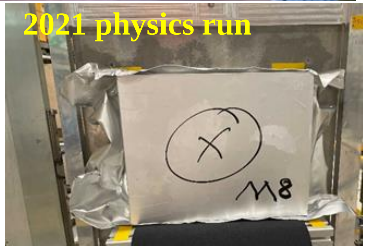
DsTau (NA65) - 2021 physics run

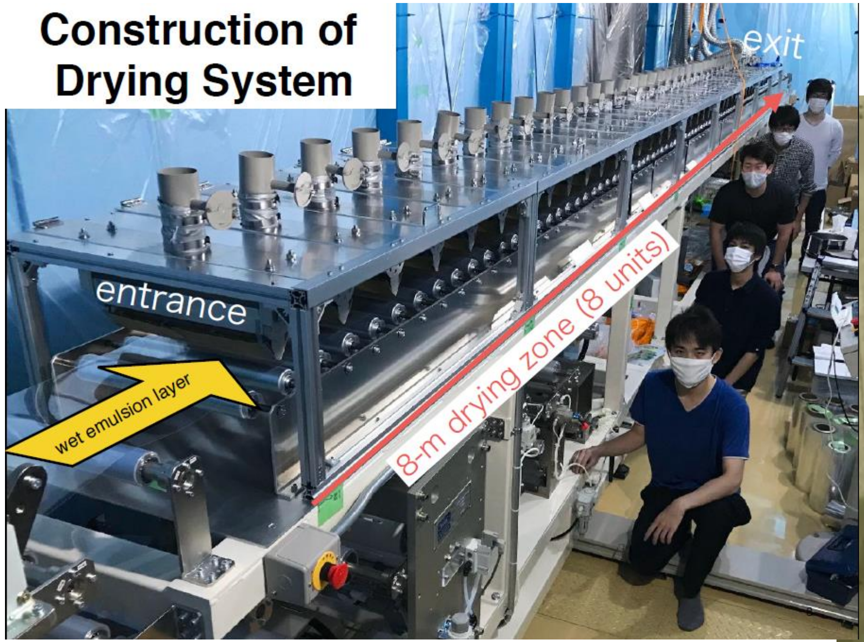
- ✓ initial, it was planned to use >200 m^2 emulsion but due to Covid19 the emulsion production is slowed down in Japan
- ✓ the number of detector modules is reduced to 110 m^2 (≃ 2200 films) – *17 modules in total*
- ✓ emulsion film size was changed at ***25 cm x 20 cm = 4 X 2018 NE size***



Film automated production facility in Nagoya

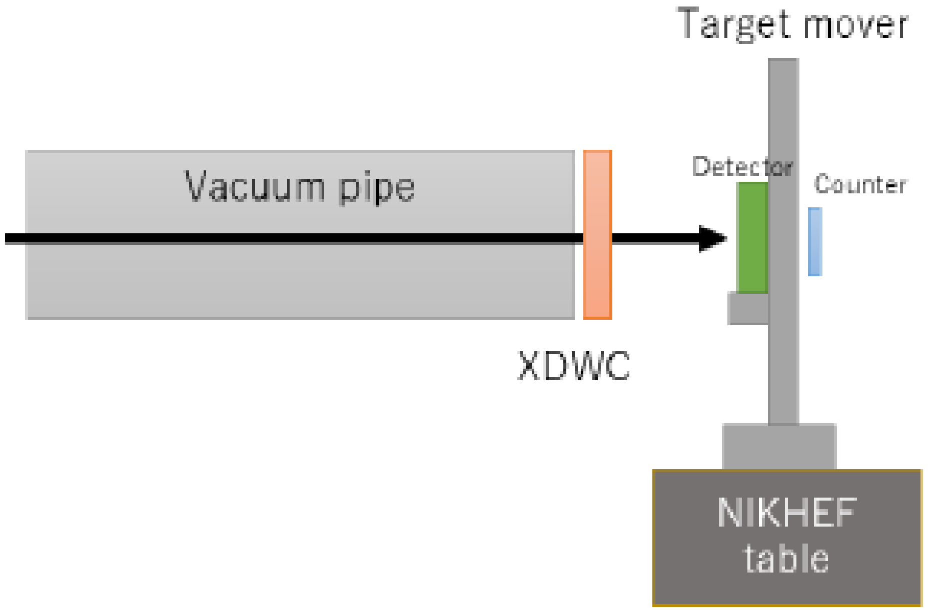
- speed production increases from about 6m^2/week to 10m^2/day

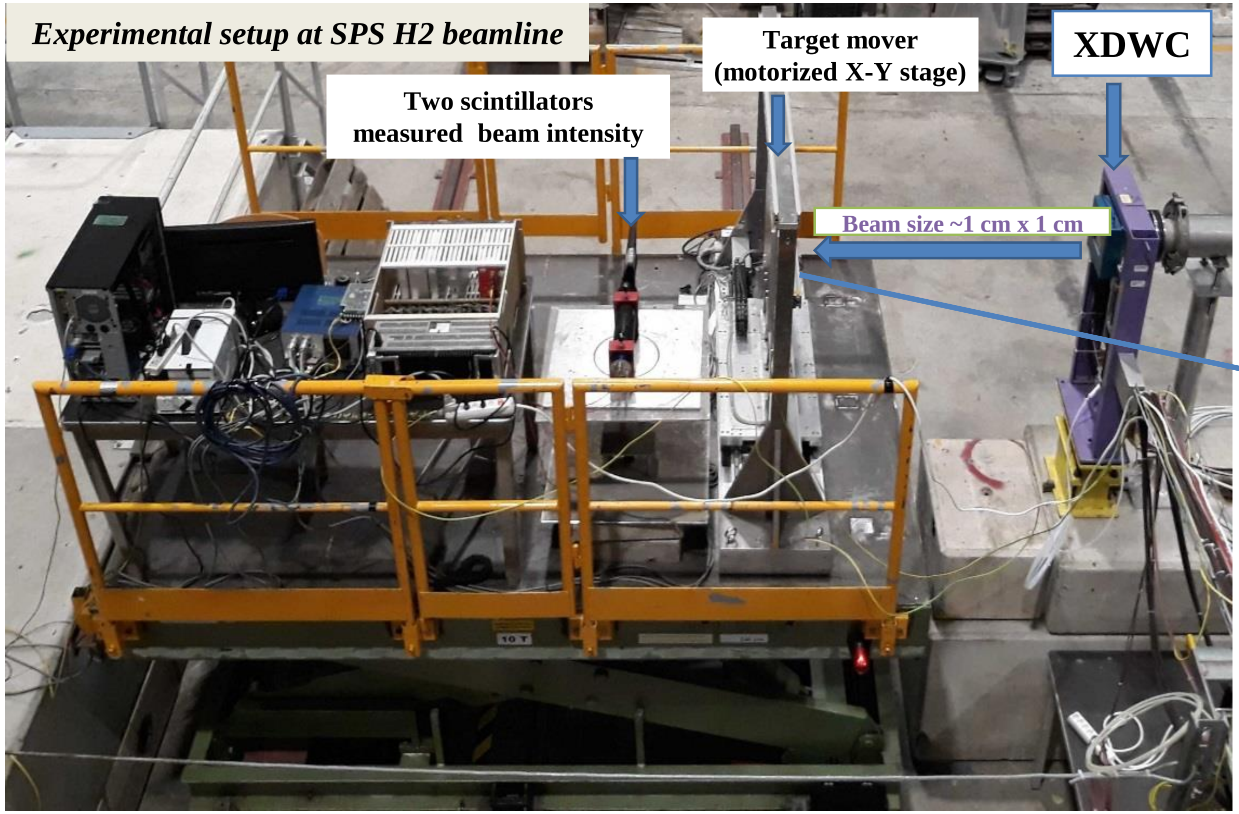


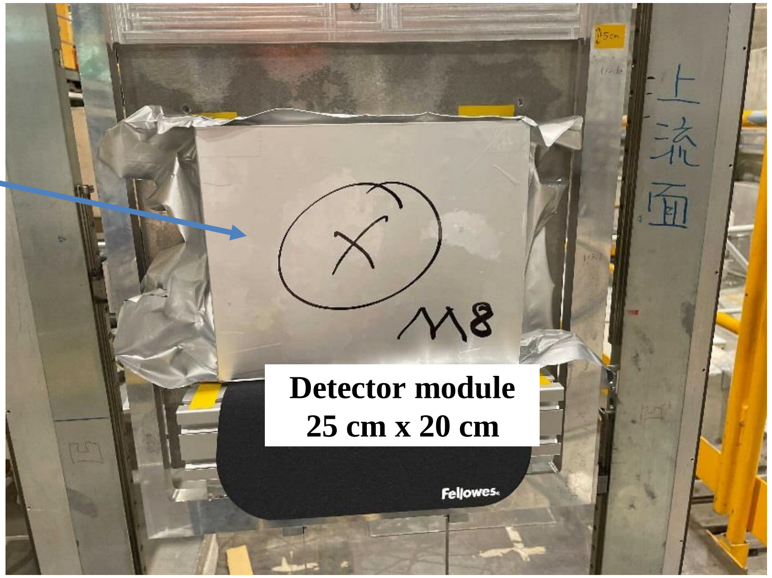


DsTau (NA65) - 2021 physics run

- ✓ new target mover
- ✓ XDWC for beam profile monitor
- ✓ Two scintillators measured beam intensity in real-time



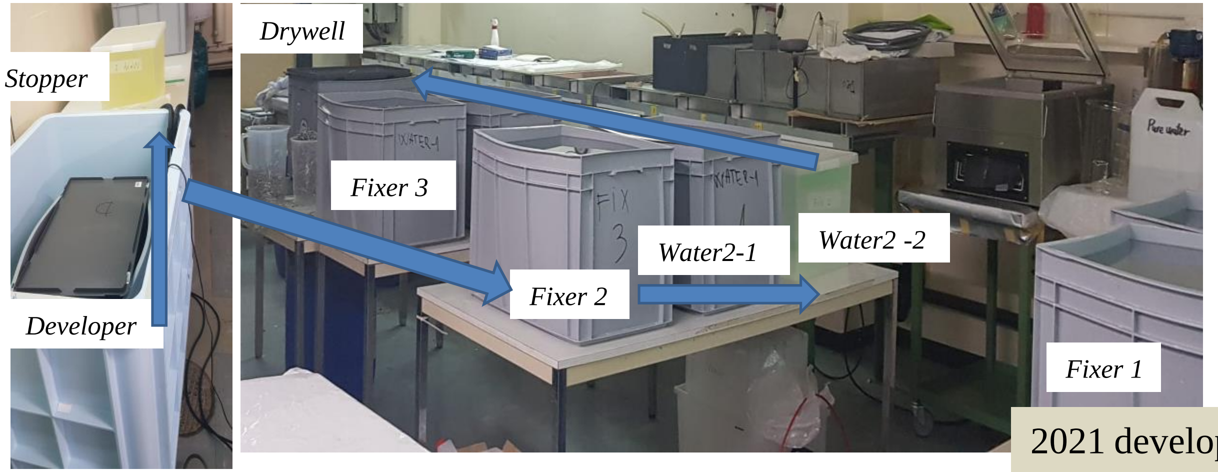




✓ ***proton beam at a density of 10^5 protons/cm^2***

DsTau (NA65) - 2021 physics run

- ✓ first time the development of nuclear emulsion film after irradiation took place at the facility from CERN
- ✓ 2021 physics run development campaign lasted 3 weeks
- ✓ ~ 2200 films were developed



2021 development facility at CERN

- ✓ **development facility was fully renovated by CERN for 2022 physics run**

Future plan runs

- ✓ **Emulsion film production**
  - ➢ Limited amount of emulsion films (≈ 100 m^2) for *2022 physics run*
    - ▪ Short beam time (*1 week*) between *12 – 19 October @ H4*

	Plan 2021	Updated plan 2022	Number of modules
2018 pilot run	50 m^2	50 m^2 (1w)	30 modules
2021 run	100 m^2	110 m^2 (2w)	17 modules
2022 run	450 m^2	110 m^2 (1w)	17 modules
2023 run	0 m^2	330 m^2 (3w)	51 modules

- ✓ ***Need an additional data taking in 2023 for 3 weeks***

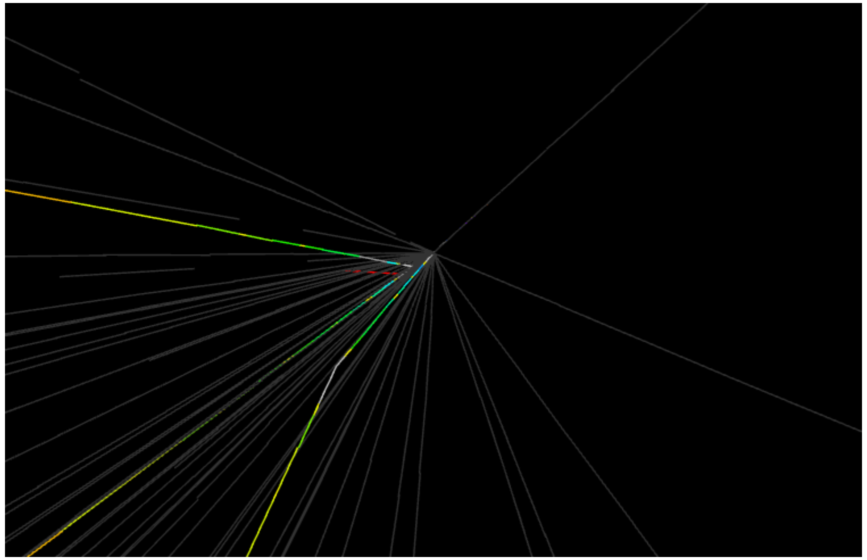
Summary

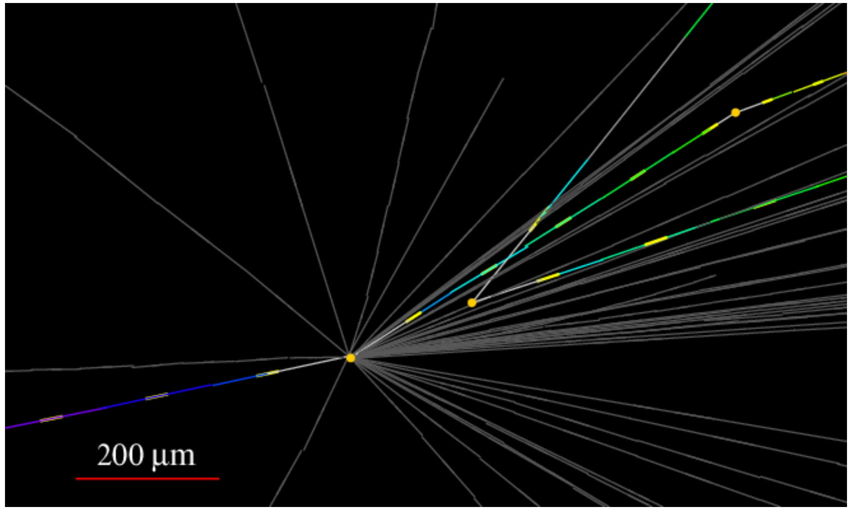
- **DsTau (NA65) goal:**
  - to detect 1000 $D_s \rightarrow \tau$ decays in 2.3×10^8 proton interactions in order to reduce the systematic uncertainty in flux measurements from >50% to 10%
  - study of open charm production

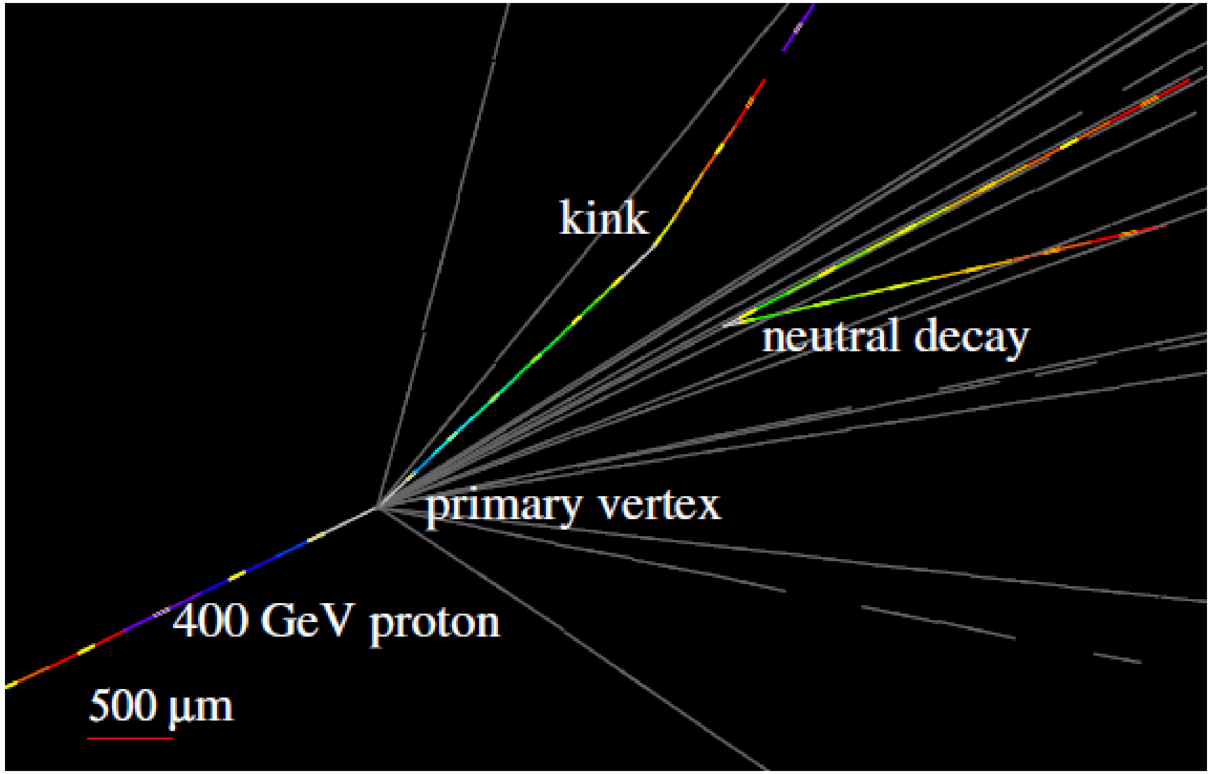
- **Current results:**
  - data reconstruction and analysis (data/MC, double charm) from 2018 pilot run are ongoing - ***first physics results will be published soon***
  - 2021 physics run, data taking campaign was successfully finished, we start data acquisition
    - 30% of planned exposure was done
    - Monte Carlo simulation with FLUKA and Geant4 soon we will start

- **Preparation for 2022 physics run** ongoing is in progress

Thank you for your attention!



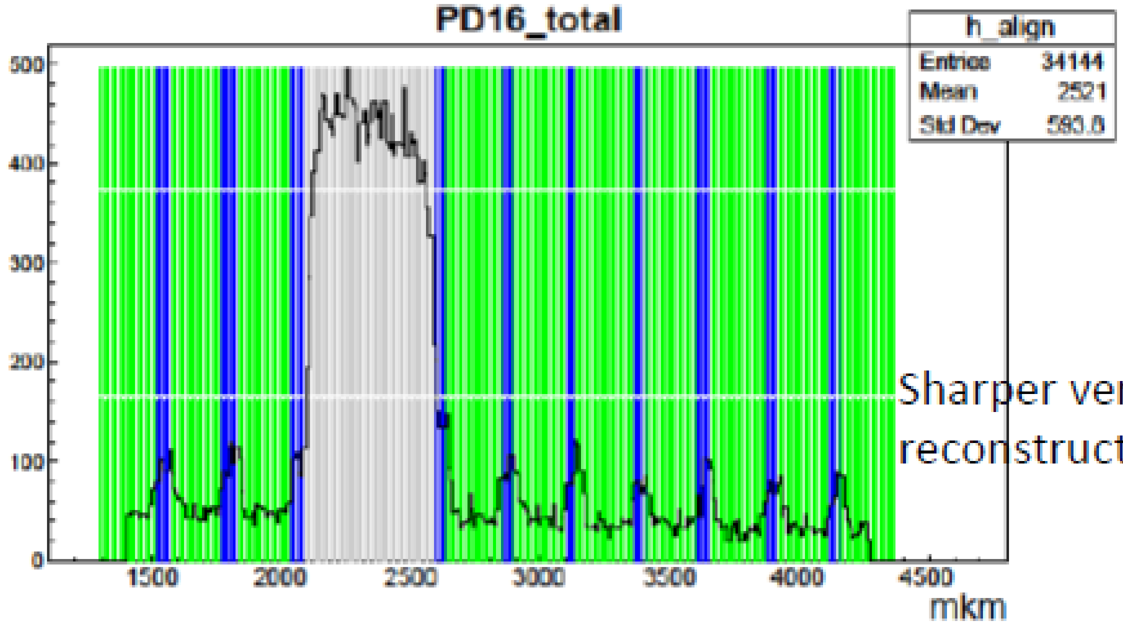




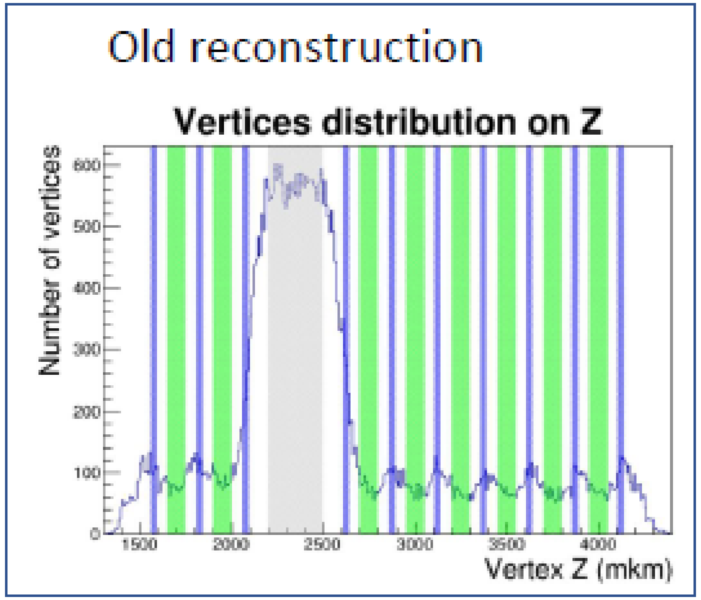
Back – up slides

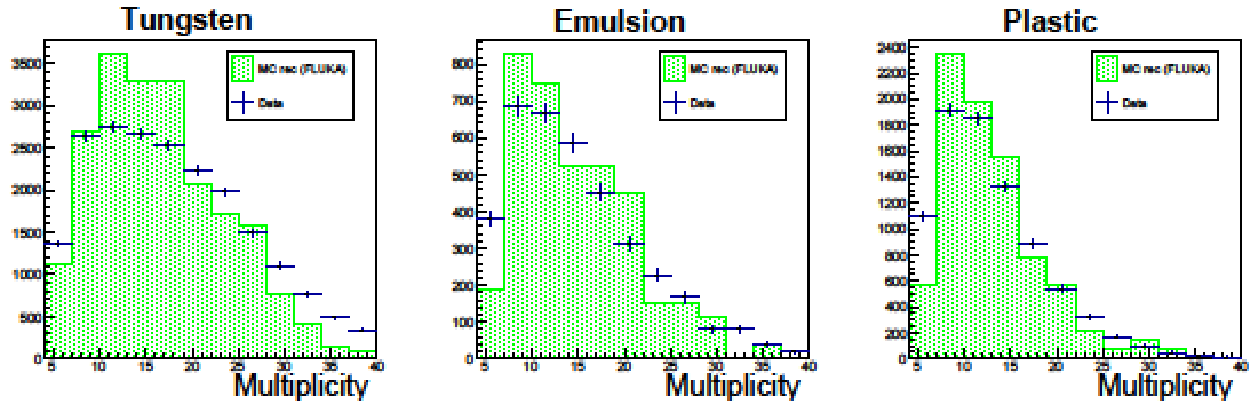
Study of Proton interaction with tungsten

- ✓ Proton interaction vertices location by fine alignment on the material boundaries.
- ✓ Secondary tracks multiplicity distribution by each detector components



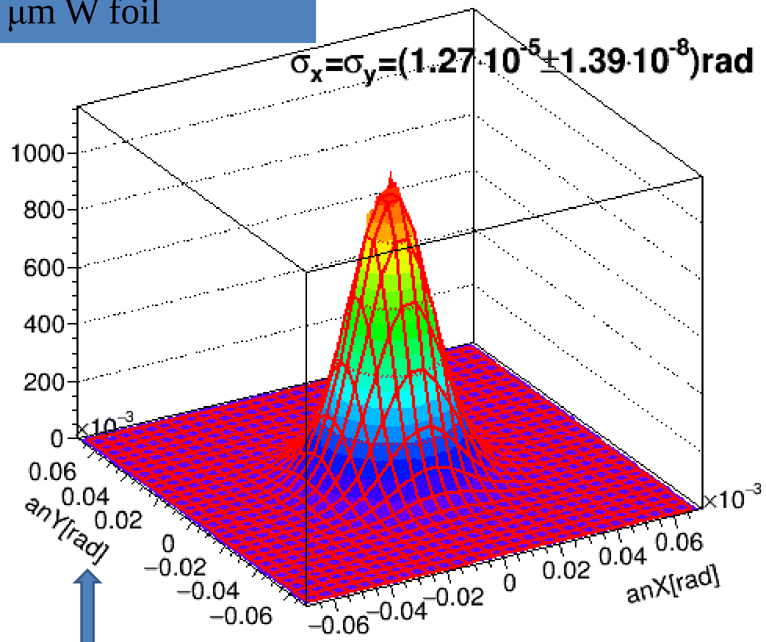
Sharper vertex Z reconstruction

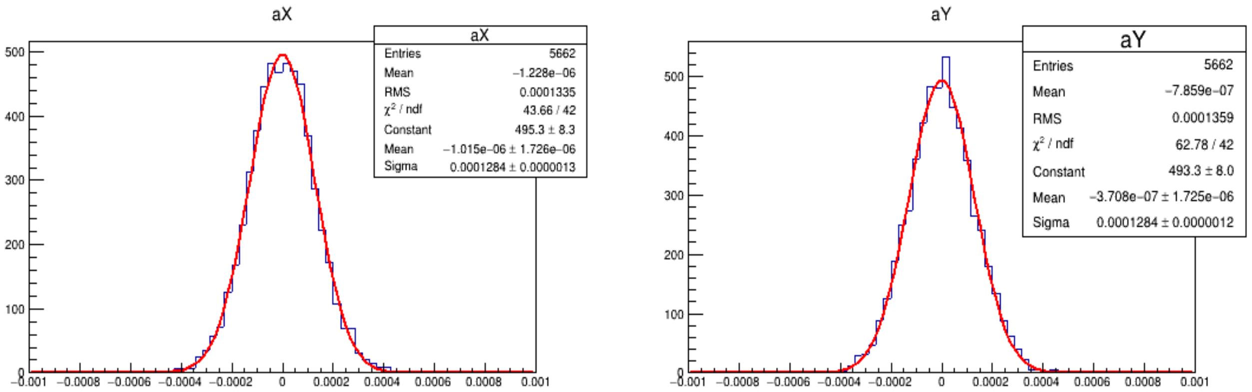




Momentum estimation by MCS (multiple coulomb scattering)

Geant4 simulation for 400 GeV/c proton on 500 μm W foil





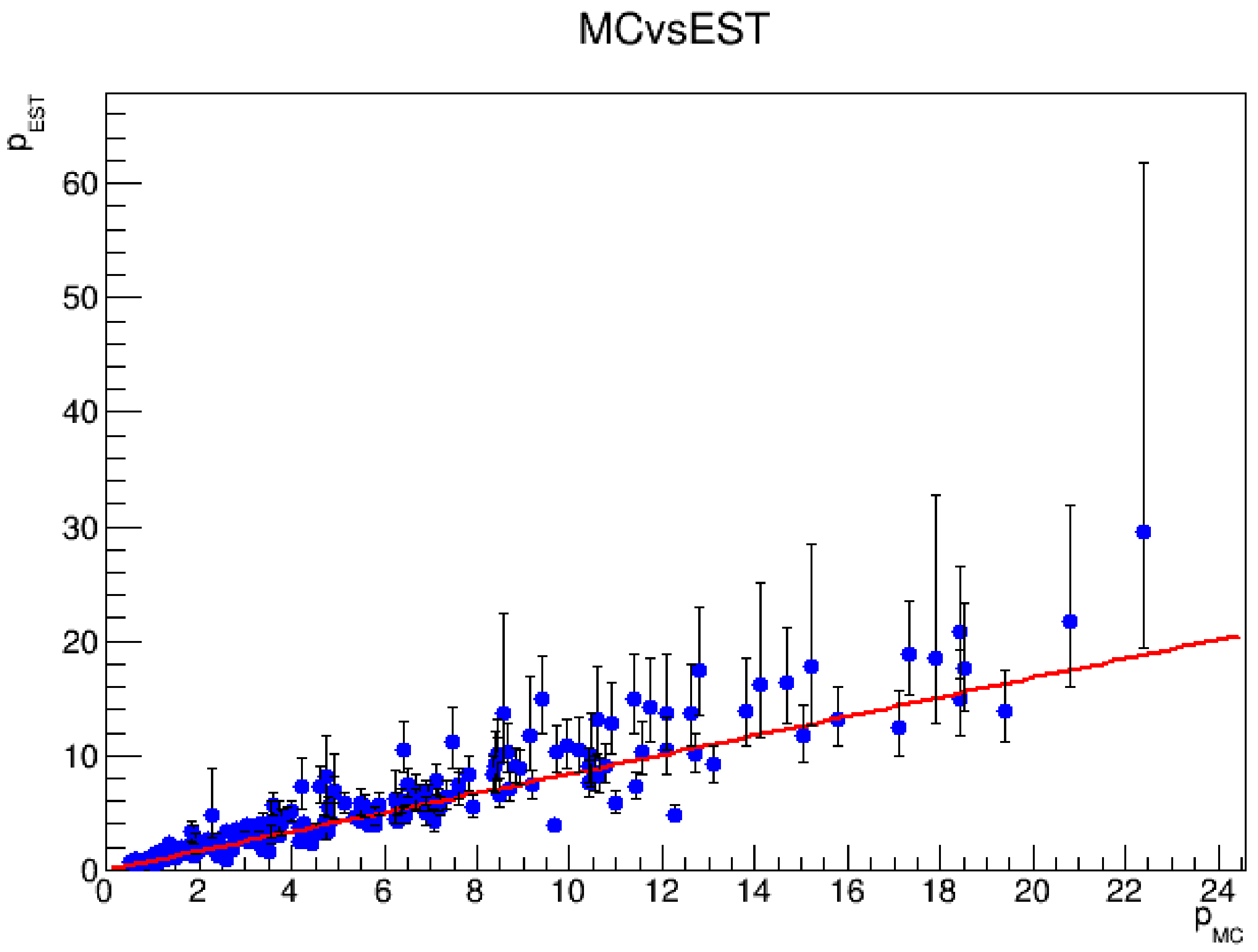
real data for 400 GeV/c

- ✓ **measurements for 30 plates, using real data**
- ✓ **$\sigma_x \approx \sigma_y = 1.28 \times 10^{-4}$ rad**

- ✓ **distribution of the projected scattering angle on the X-plane VS projected angle on the Y-plane**
- ✓ **from Gauss fit →σ is determined → momentum was estimated**

For momentum > 30 GeV/c, scattering angles < angular resolution

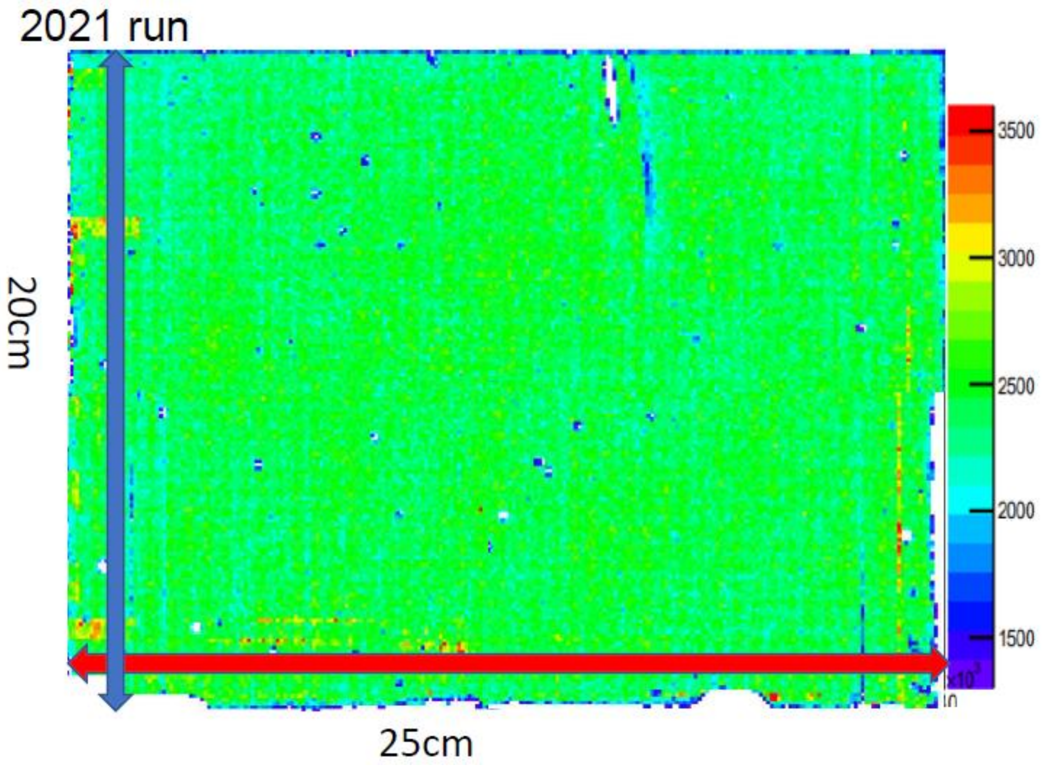
MC momentum VS Estimated momentum



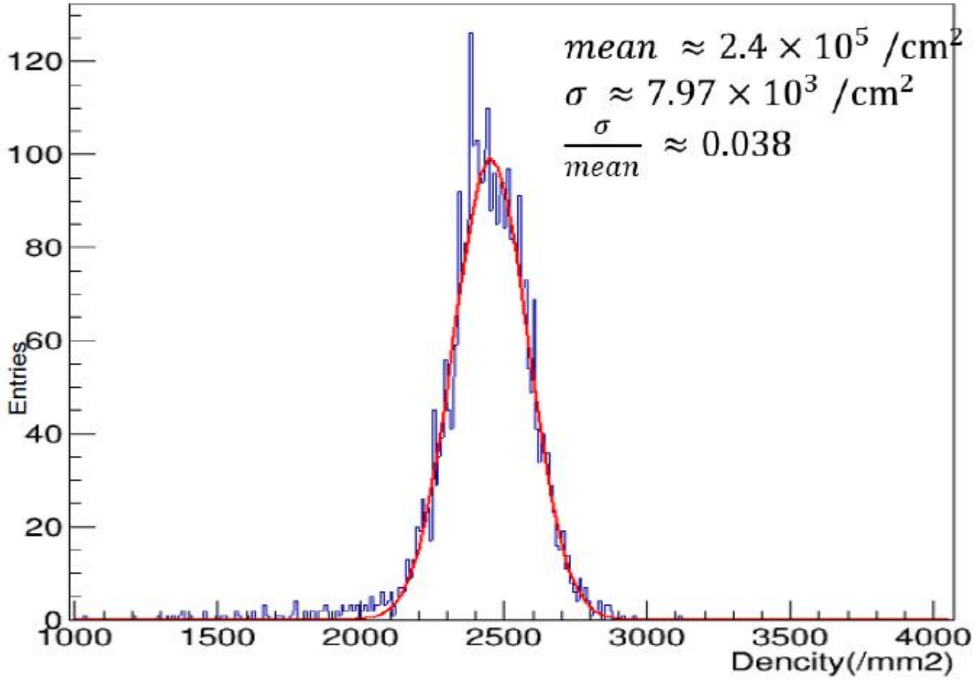
- ✓ Fit with line $p_{est} = m * p_{MC}$, where m = 0.83 ± 0.01 (~40°)
- ✓ For larger MC momenta, estimated momenta has larger errors

DsTau (NA65) - 2021 physics run

- ✓ 17 modules were exposed
  - 12 tungsten and 5 molybdenum targets for analysis part
- ✓ all modules are ready to be scanned & scanning started

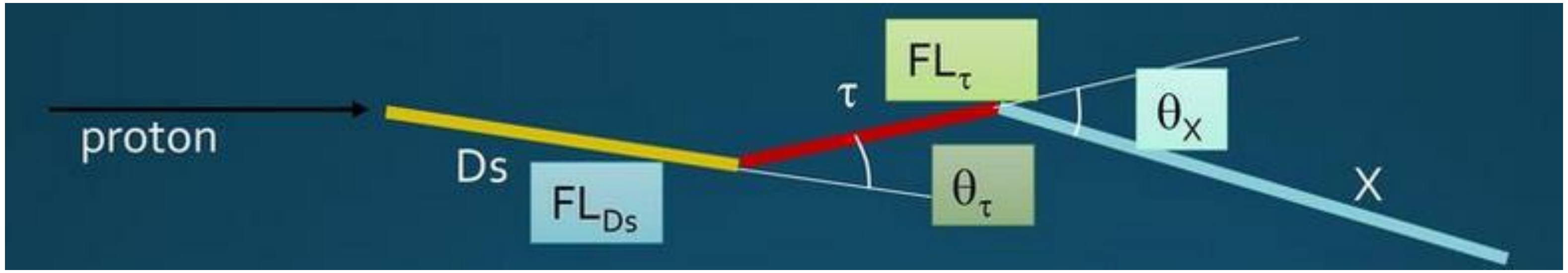


track density uniformity fitted by a Gauss function

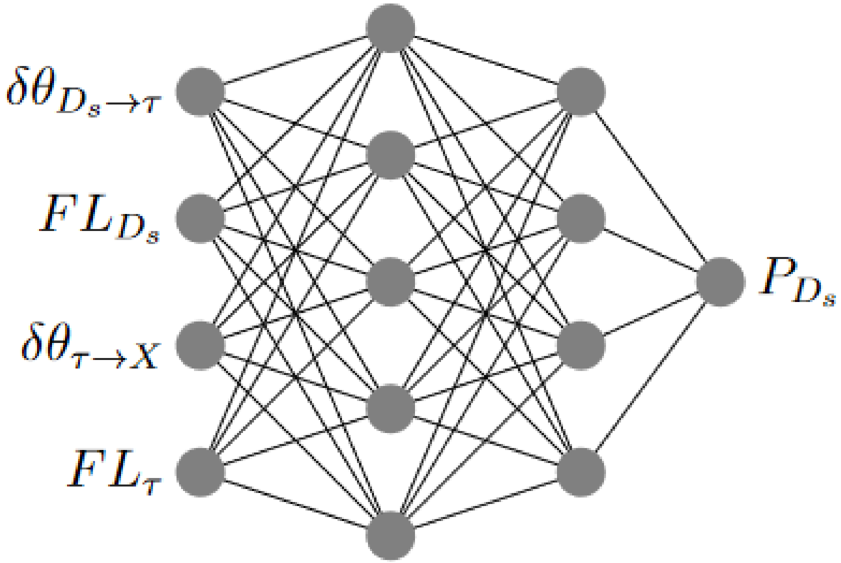


D_s momentum reconstruction

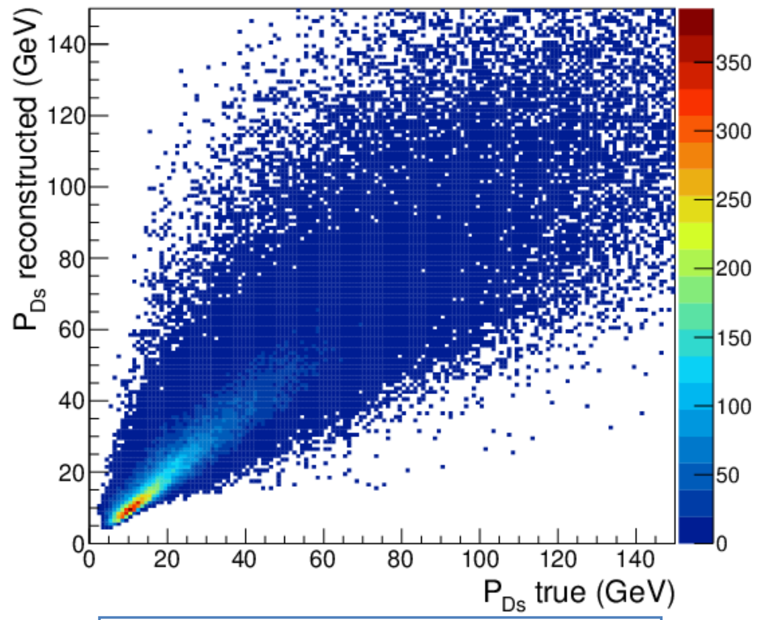
- ✓ Ds momentum directly measurement it is difficult due to short lifetime
- ✓ DS momentum cannot be directly determined and momentum is reconstructed by topological variables



- ✓ The variables are put in a neural network to determine momentum resolution

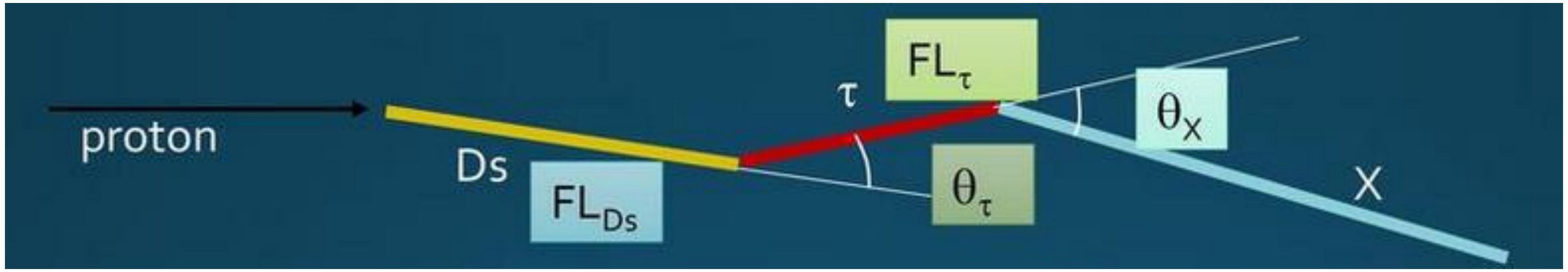


D_S momentum reconstruction by neural network



Momentum resolution Δp/p = 20%

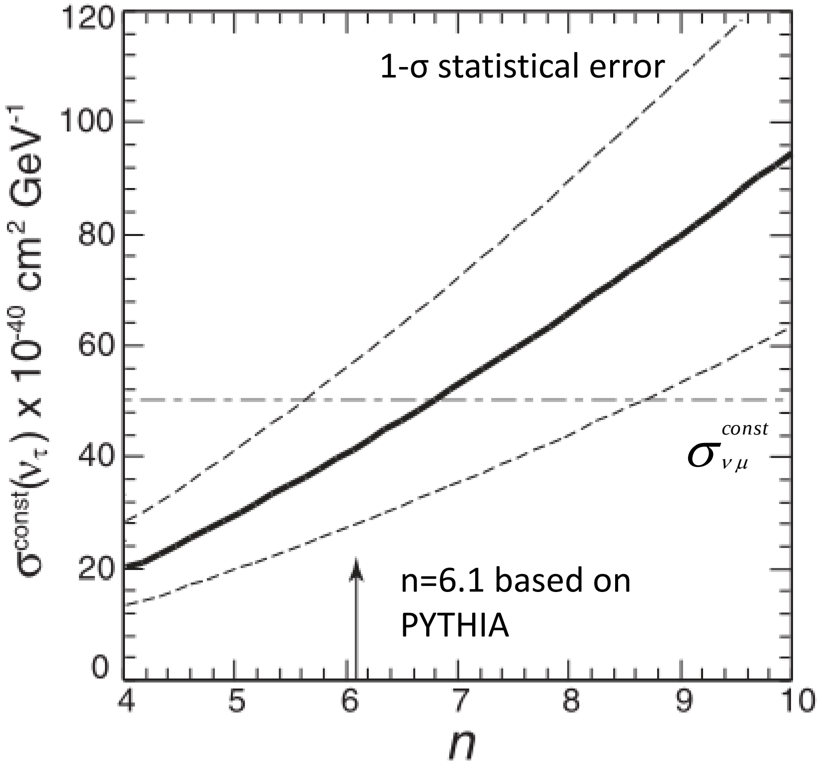
D_s efficiency detection



Selection Criteria	Efficiency (%)
(1) Flight length of $D_s \geq 2$ emulsion layers	77
(2) Flight length of $\tau \geq 2$ layers & $\Delta\theta(D_s \rightarrow \tau) \geq 2$ mrad	43
(3) Flight length of $D_s < 5$ mm & flight length of $\tau < 5$ mm	31
(4) $\Delta\theta(\tau) \geq 15$mrad	28
(5) Pair charm: 0.1 mm < flight length < 5 mm (charged decays with $\Delta\theta > 15$ mrad or neutral decays)	20

Results from DONuT

ν_τ CC cross section as a function of the parameter n



Using PYTHIA-derived value of n=6.1

$$\sigma^{const}_{\nu\tau} = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38}\, cm^2 GeV^{-1}$$

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

Phenomenological formula for differential production cross-section of charmed particles

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

No published data giving n for D_s produced by 800 GeV proton interactions

Systematic uncertainties	
D_s differential cross section (x_F dependence)	~0.50?
Charm production cross section	0.17
Decay branching ratio	0.23
Target atomic mass effects (A dependence)	0.14

D_s differential cross section

Parametrization used in DONUT

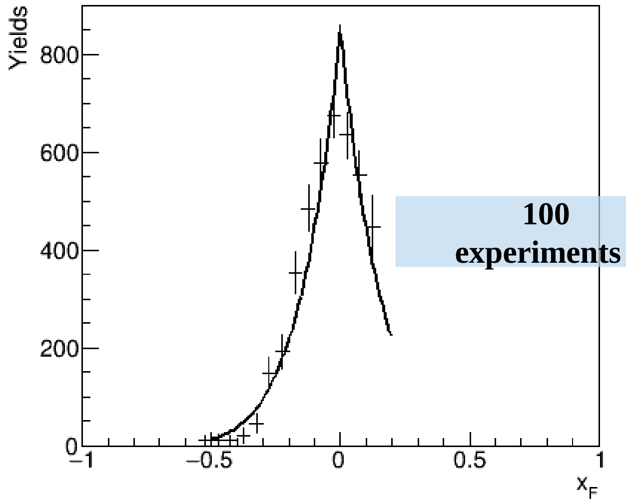
$$\frac{d^2\sigma}{dx_F\, dp_T^2} \propto \underbrace{(1-|x_F|)^n}_{\text{longitudinal dependence}} \underbrace{\exp(-bp_T^2)}_{\text{transverse dependence}}$$

x_F is Feynman x ($x_F = 2p^{CM}_Z/\sqrt{s}$) and p_T is transverse momentum

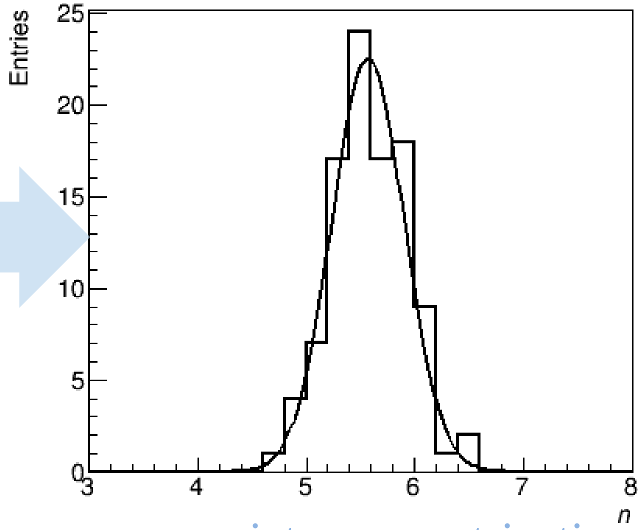
reconstructed x_F
(corrected by the efficiency)

an experiment with 1000 events
→ estimate of parameter *n*

estimated parameter *n*



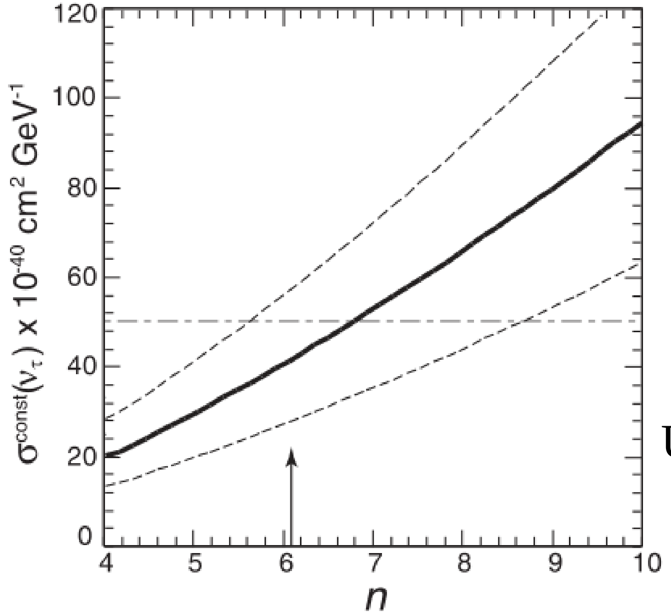
100 experiments



For future measurement, a more appropriate parametrization will be used

Results from DONuT

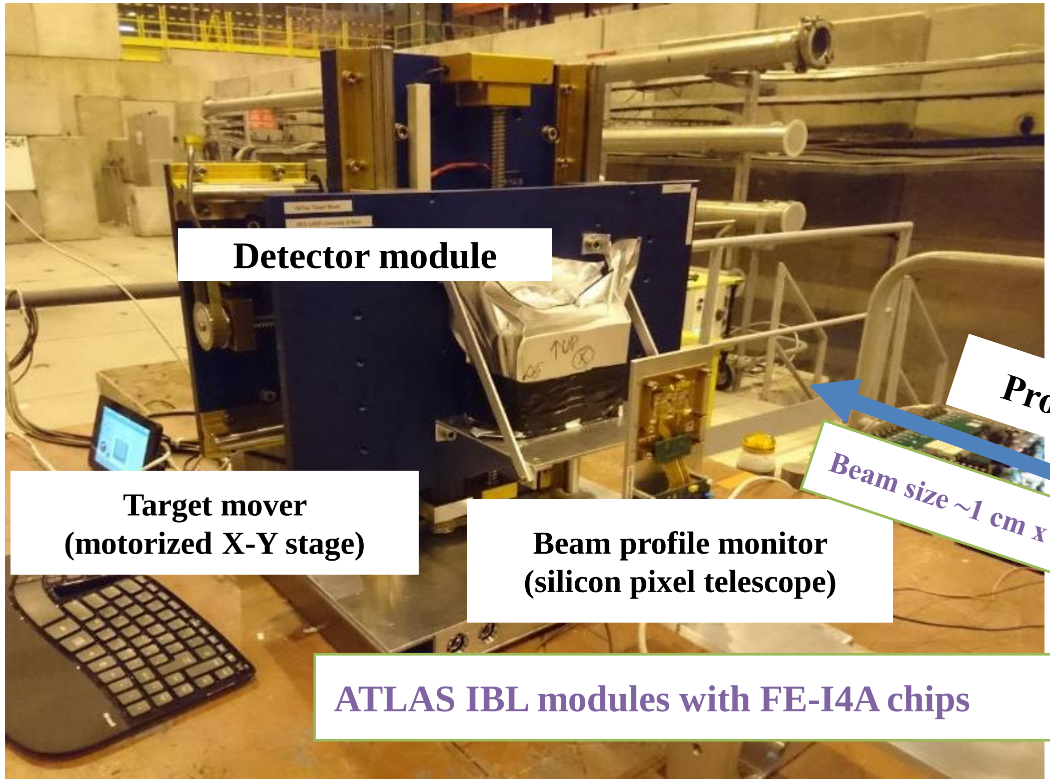
ν_τ CC cross section as a function of the parameter n



Using PYTHIA-derived value of n = 6.1

Experimental set-up – 2018 pilot run

Experimental setup at H4 beam line



scintillator for intensity driven control