Experiment DsTau (NA65) - study of tau neutrino production at CERN SPS

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on behalf of DsTau/NA65 Collaboration

ICHEP 2020, 28/07-06/08, Prague, virtual conference

Tau neutrino and lepton universality

NA65 DsTau

❖ Tau neutrino is one of the least studied particles

- ➢ few measurements only

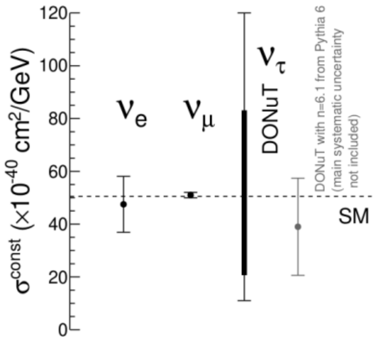
  direct ν_τ beam: DONuT

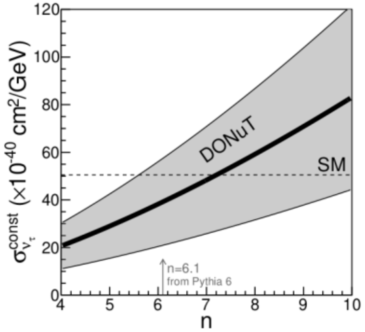
  Oscillated ν_τ: OPERA, Super-K, IceCube

- ➢ Cross section error > 50% caused by ***systematic uncertainty in ν_τ production***

❖ Lepton Universality test in neutrino scattering

- ➢ Hint on ***LU violation from B decays***, $\bar{B} \to \tau \nu_\tau D^{(*)}$. New physics in tau sector?
- ➢ ***A precise measurement of ν_τ cross-section would provide a unique and complementary information***

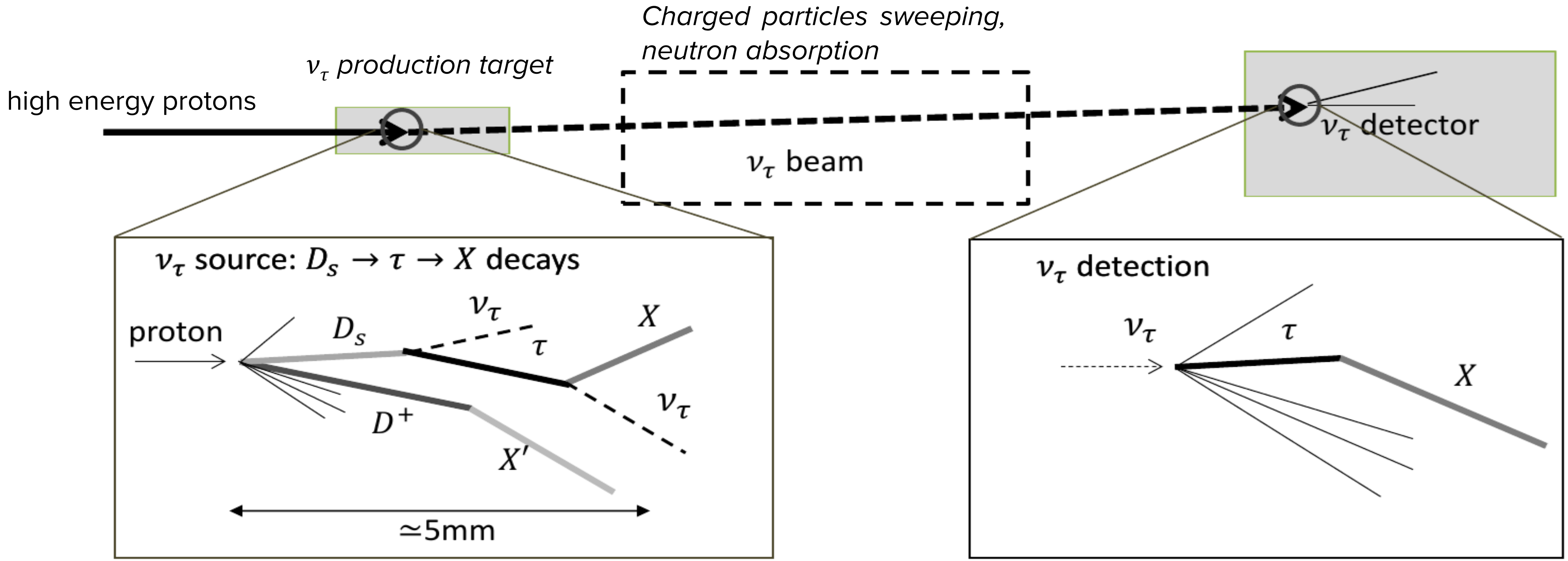




ν_τ cross-section uncertainties in DONuT

- ➢ **Statistics**: ~33%, 9 events were detected → to be improved by neutrino experiments (FASER, SHiP, etc.)
- ➢ **Production**: >50% due to lack of differential production cross section data and 33% caused by other reasons → to be improved by DsTau

ν_τ cross section measurement with accelerator



ν_τ production study: DsTau

- D_S production differential cross-section will be measured
- The systematic uncertainty in ν_τ production will be decreased from present ~50% to 10%.

ν_τ detection: SHiP etc

- Statistical uncertainty **33%** in DONuT will be reduced to the **2%** level in future experiments

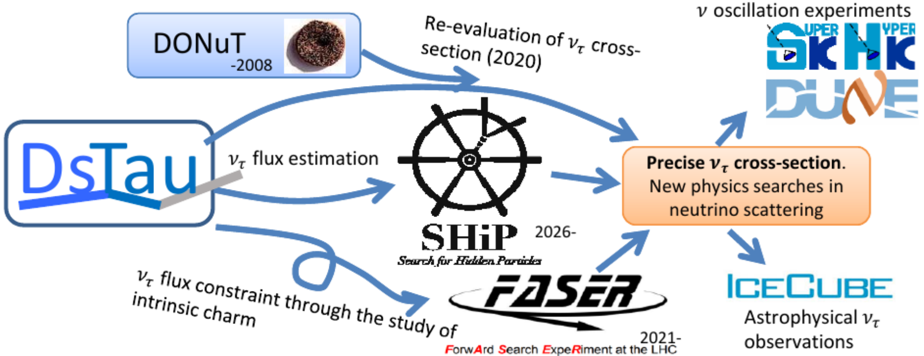
DsTau experiment at CERN SPS

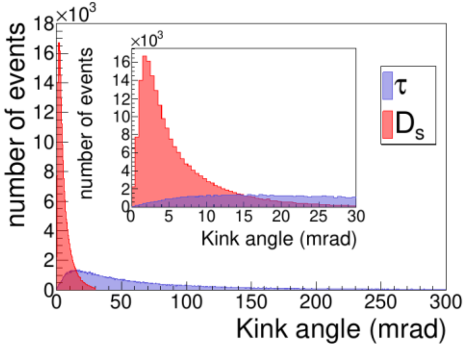
Goals:

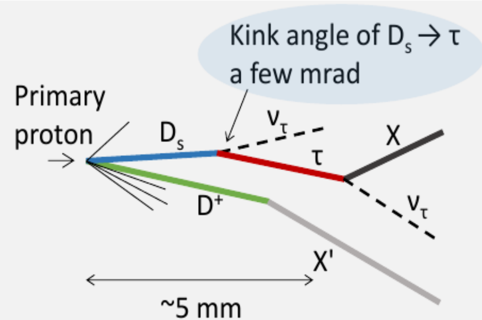
- **Study of ν_τ production for future tau neutrino experiments**
  - First measurement of D_S double differential production cross section
  - Provide 0(10 GeV) ν_τ production with beam dump method
  - To reduce uncertainty of ν_τ flux from >50% to 10%
- **Charm physics, intrinsic charm component in proton**

Principles of the experiment:

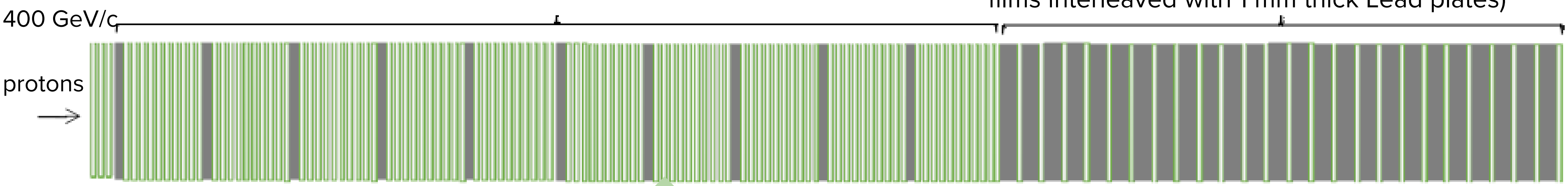
- Detection of **“double-kink+charm decay”** topology within several mm
- 4.6 x 10^9 400 GeV/c protons → 2.3 x 10^8 interactions in W/Mo → 10^5 charm pairs → **1000 D_S → τ → X decays**

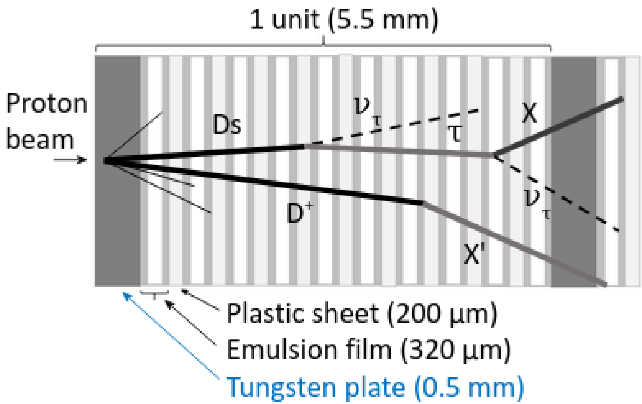


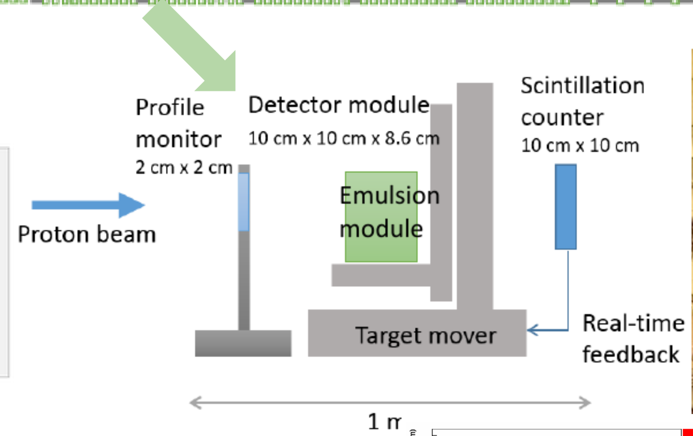


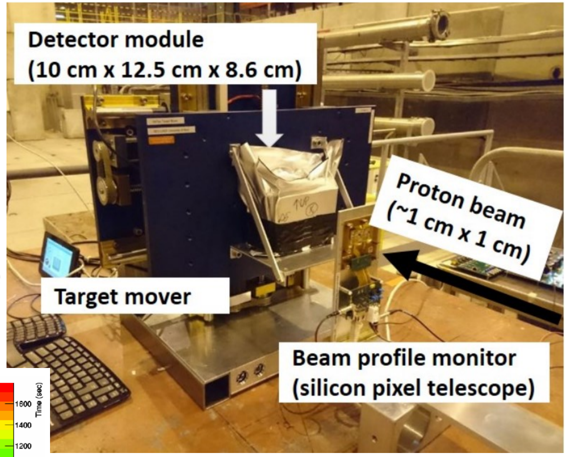


Experimental setup

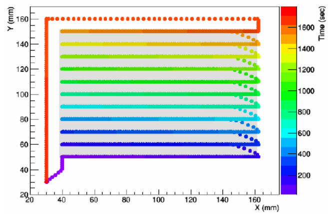








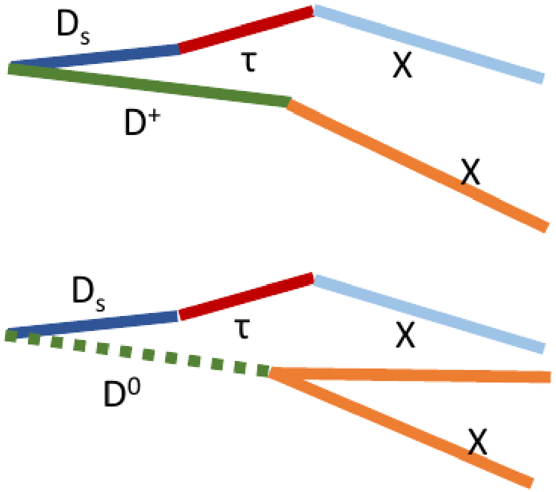
370 modules are to be exposed and analysed



Module movement wrt proton beam position

Signal and background

Signal: $D_s \to \tau$ decay with small kink ~7 mrad

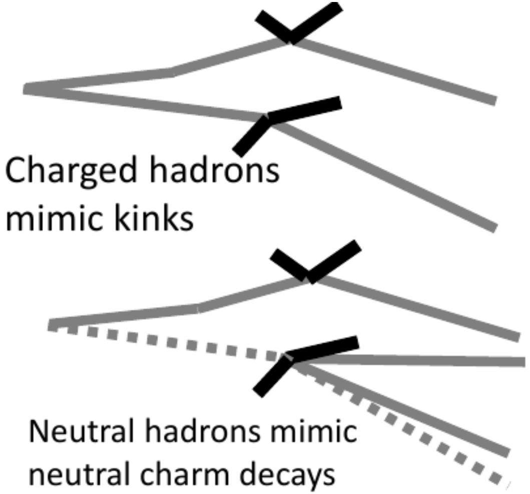


Detection efficiency = 20%, estimated with Pythia 8.

Signal probability 2.2x10^{-7}/proton

Expected number of signal events: 1000

Main background: interactions of secondary hadrons (products of proton interactions) with no nuclear fragments detected



Background probability estimated by FLUKA.

$$P_{BG}^{charged} = 1.3 \pm 0.4 \times 10^{-9} / \text{ proton}$$
$$P_{BG}^{neutral} = 2.7 \pm 0.8 \times 10^{-9} / \text{ proton}$$

Expected number of BG events:18

Project schedule

NA65 DsTau

Feasibility study 2016
- Test of detector structure

Test beam 2017
- Improved detector structure
- Refine exposure scheme

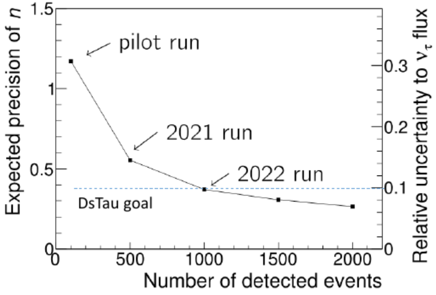
Pilot run 2018
- 1/10 of the full-scale experiment
- 30 % uncertainty on flux
- Revise the DONUT result
- Charm physics

We are here

Physics run 2021-2022
- Full scale experiment
- Aiming at collecting 1000 events
- 10 % uncertainty on flux

	# of modules	Emulsion films (m^2)
Pilot run 2018	30	49
Physics run 2021*	150	246
Physics run 2022*	190	312

*2 weeks each, pilot run exposure speed is quick enough



target	# of proton interactions	with charm pairs	Detected $D_s \to \tau \to X$
W 0.5 mm	1.08 x 10^8	1.95 x 10^5	~530
Mo 1.0 mm	1.41 x 10^8	2.10 x 10^5	~500

Emulsion production

From manual production for Pilot run 2018

Film production facilities in Nagoya and Bern

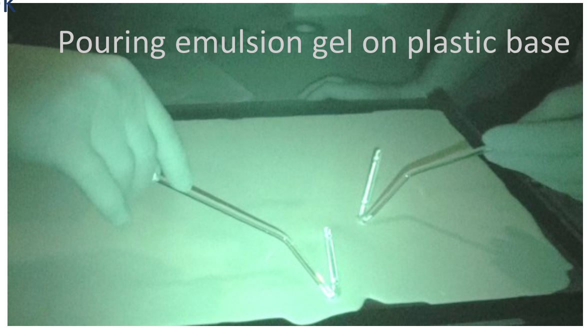
Nagoya - 5.3 m^2/week

Bern - 7 m^2/week

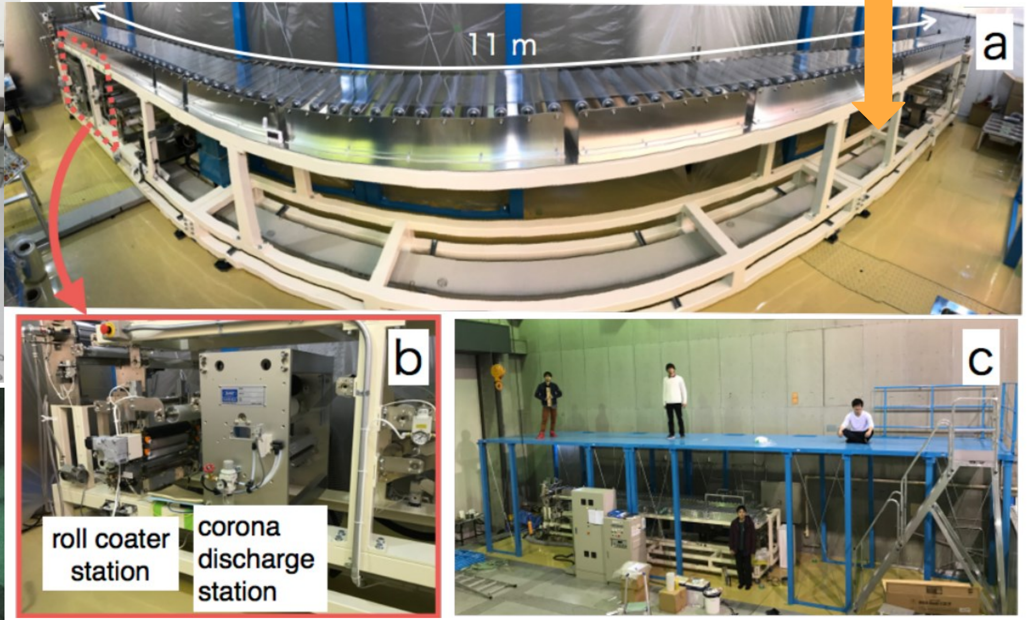
Emulsion

Base

Emulsion



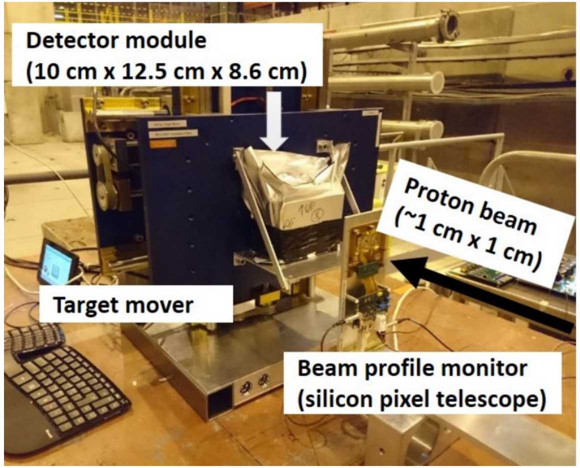
to automated production for 2021-2022 runs



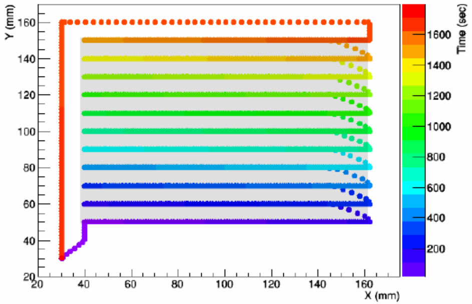
Nagoya - 12.5 m^2/day, would be ready for a production test in September 2020

Proton beam exposure at the SPS-H2

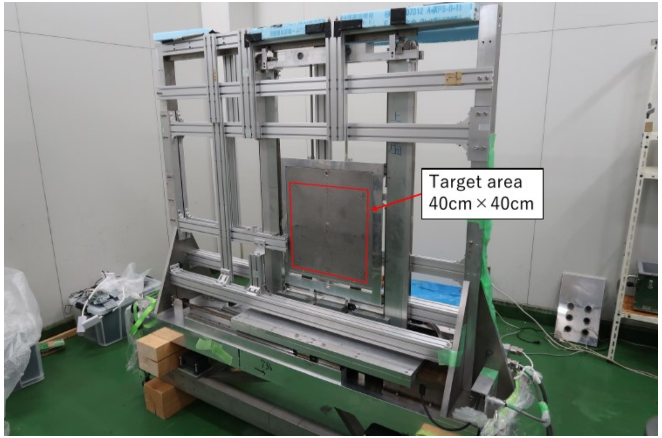
Target mover used during 2016-2018



Module movement wrt proton beam position

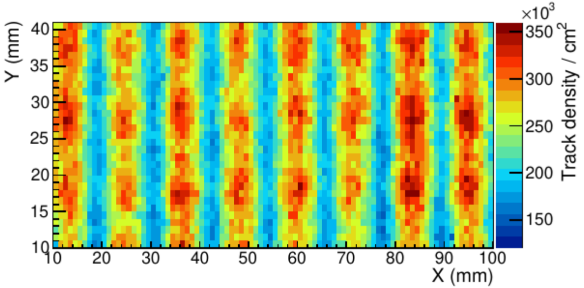


Target mover for 2021-2022 runs

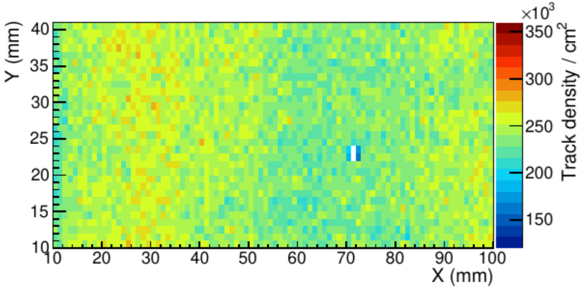


- 30 modules (12.5 cm x 10 cm) exposed in 23rd-27th August 2018
- 0.5-1 h per module 10^5 protons / cm^2 → 1.25×10^7 protons / module

Constant speed (2016)



Intensity driven control (2017-2018)



Analysis steps

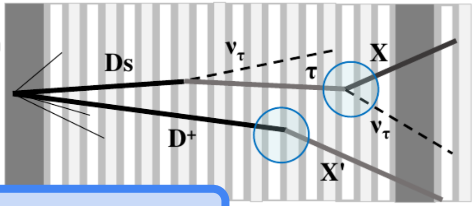
NA65 DsTau

Step 1

- Fast full area scanning
- Recognition of track segments in the emulsion layers which are combined in tracks offline
- Select decays with $\Delta\theta > 20$ mrad

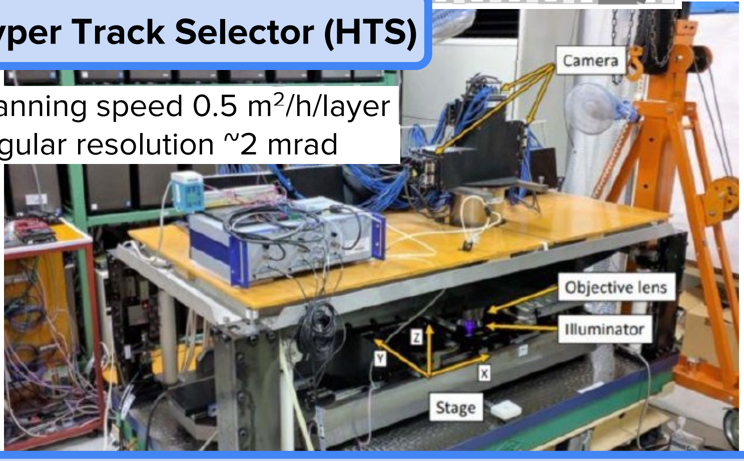
Full area scanning for 2018 pilot run was completed

Proton beam



Hyper Track Selector (HTS)

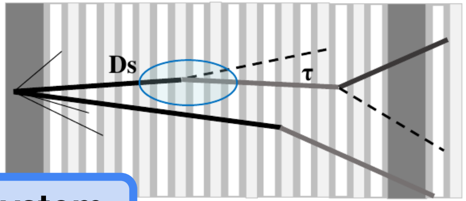
Scanning speed 0.5 m^2/h/layer
Angular resolution ~2 mrad



HTS-2 with speed of 2.5 m^2/h/layer is under construction

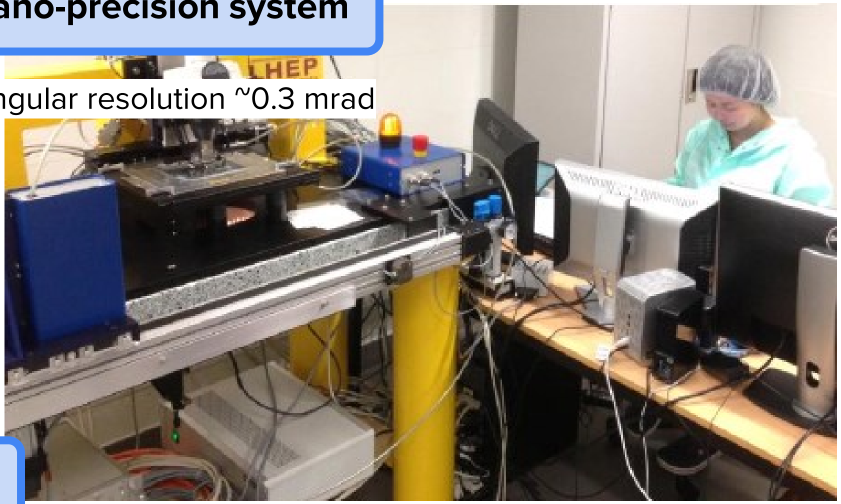
Step 2

- Precision scanning of preselected candidates to detect $D_s \rightarrow \tau$ decays (a few mrad)



Nano-precision system

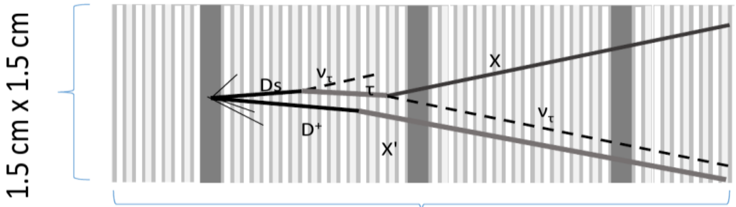
Angular resolution ~0.3 mrad



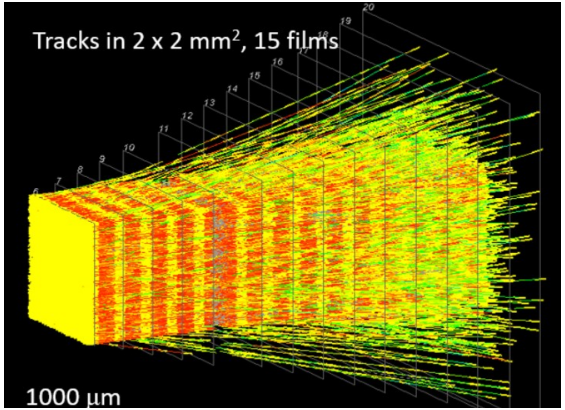
Data reconstruction: tracking, alignment

DsTau is triggerless experiment registering primary protons and their interactions at the track density level of 10^5-10^6 tracks/cm^2.
Unique spatial resolution of emulsion detectors allows to efficiently recognise the tracks and vertices.

Processing in subvolumes 1.5 cm x 1.5 cm x 30 plates

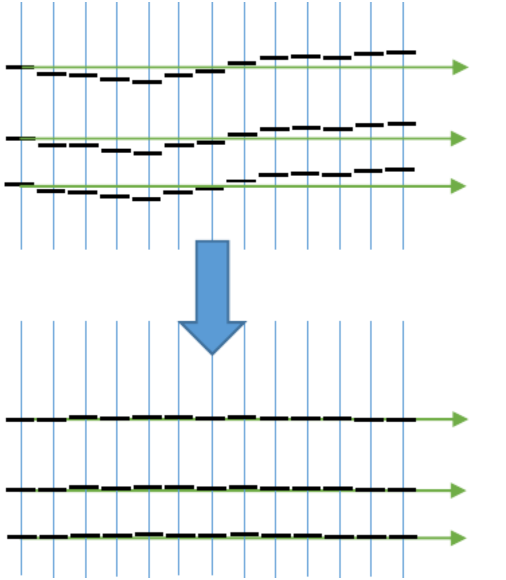


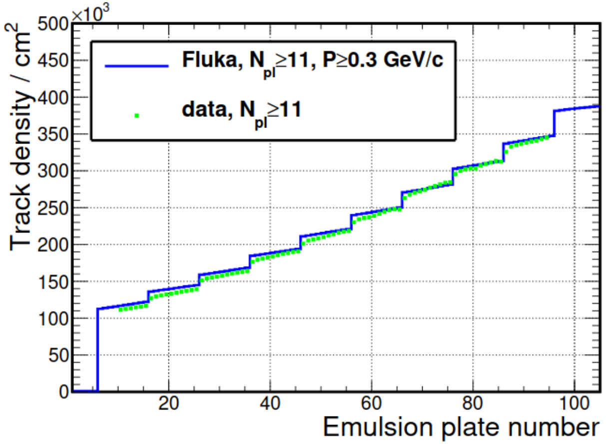
30 films
(two tungsten plates to reject low momentum daughter candidates)

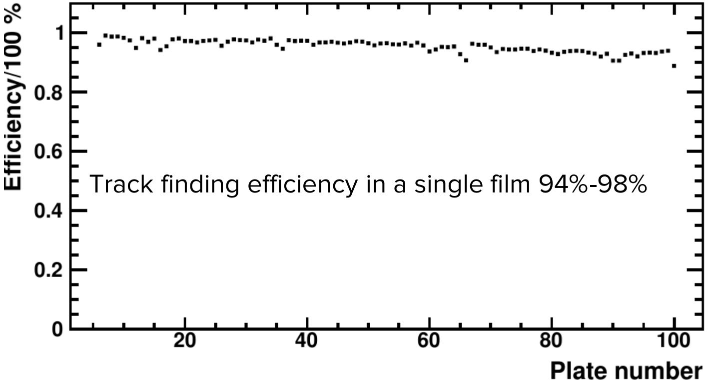


Alignment with proton beam tracks, 100 tracks/mm^2

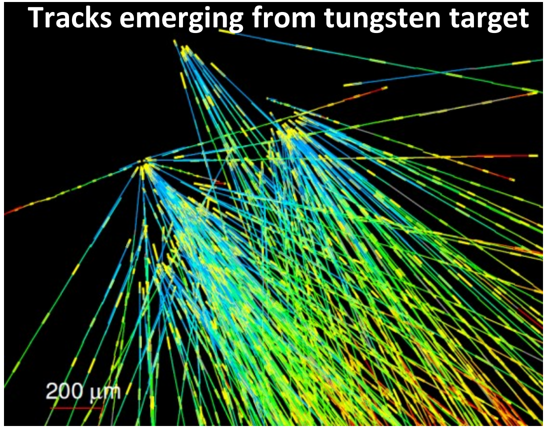
Residual of track segments to fitted line (RMS) $\simeq$ **0.4 μm**



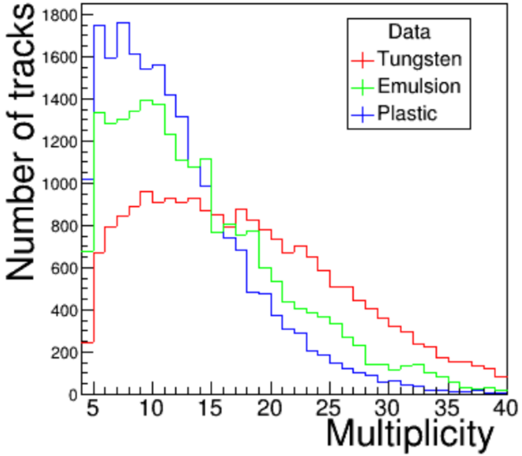




Data reconstruction: vertexing

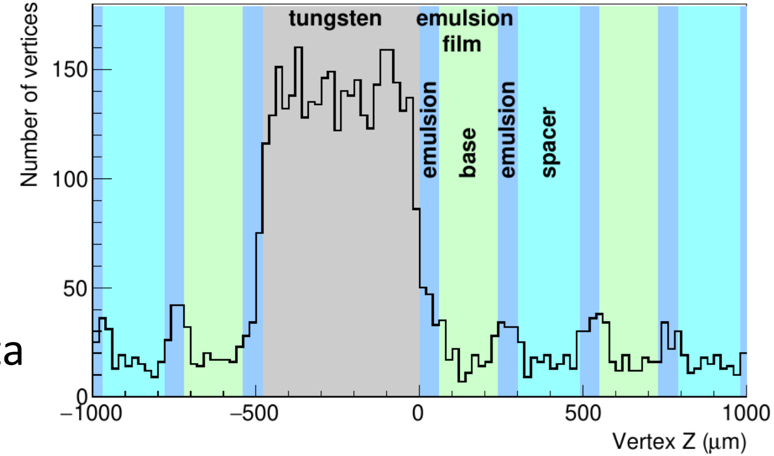


Vertex density
~500/cm^2/ tungsten plate



We are performing comparison between data and different generators

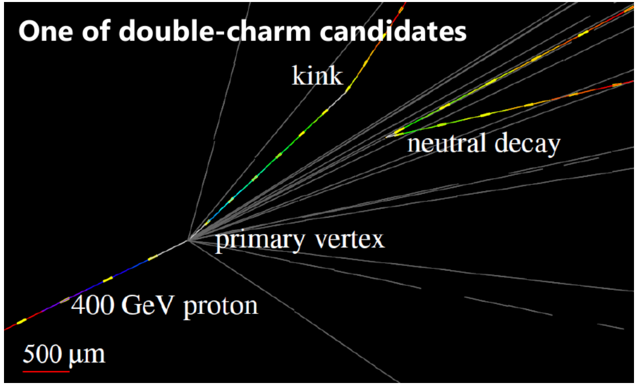
Reconstructed vertex position



Fine detector structure is observed by reconstructed vertices

Data reconstruction: charm decay search

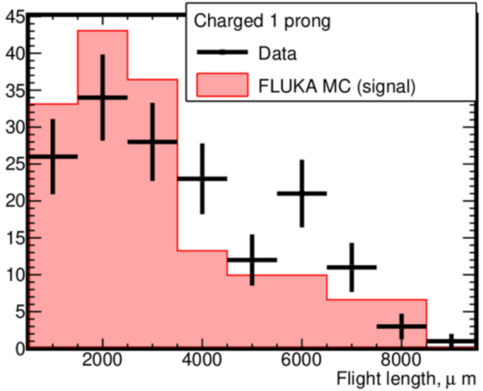
Subsample of 2016 and 2018 runs were analysed
Double charm event search: a charged 1-prong decay + another charged or neutral decay

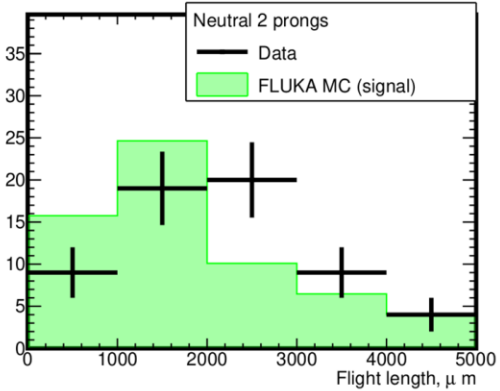


- >34.2 x 10^6 protons analysed
- 272,120 proton interactions reconstructed (147,236 in tungsten)
- 159 events (115 in tungsten) with double decay topology detected

	Observed	Expected	
Vertices in tungsten	147,236	155,135	
		Signal	Background
Double decay topology	115	80.1±19.2	12.7±5.0

- Flight length distribution shows that **our charm analysis chain works**

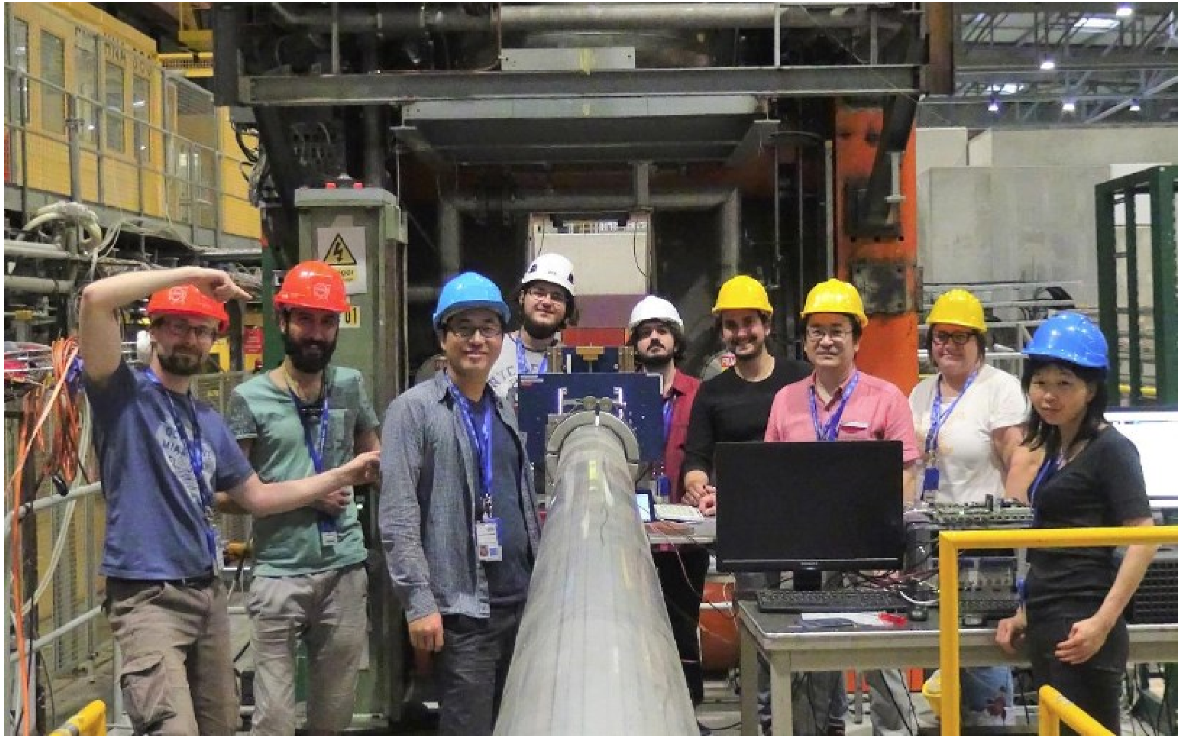




Summary

- DsTau project was proposed at the CERN SPS to study ν_τ production (CERN-SPSC-2017-029, SPSC-P-354, arXiv:1708.08700), was **approved as NA65** in July 2019
  - Detect 1000 $D_S \to \tau \to X$ decays in 2.3 x 10^8 400 GeV/c proton interactions employing emulsion detector with a spatial resolution of 50 nm
  - Reduce the systematic uncertainty in the ν_τ cross section measurement from >50% to 10%
  - Study charm particle production which will provide important input to QCD studies
- **2018 pilot run successfully performed, about 10% of data were collected, analysis is underway** (JHEP01(2020)033, arXiv:1906.03487)
  - Fast full area scanning is completed
  - Data analysis is ongoing (data/MC comparison, systematic double charm candidates search)
- **Preparing for physics run 2021/2022 (CERN NA65)**
  - Detector geometry optimization
  - Fast emulsion production line preparation
  - Faster readout preparation

Thank you for attention!



DsTau team during 2018 pilot run

Collaboration

Japan
Aichi University of Education
Gifu University
Tohoku University
Kobe University
Kyushu University
Nagoya University

Romania
Institute of Space Science Bucharest

Russia
Joint Institute for Nuclear Research

Switzerland
CERN
University of Bern

Turkey
Middle East Technical University

BACKUP SLIDES

Future tau neutrino measurements

Opportunities to measure ν_τ cross section

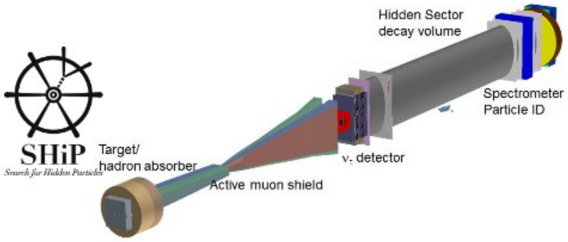
- **SHiP**: high statistics ν_τ measurement at the SPS beam dump facility

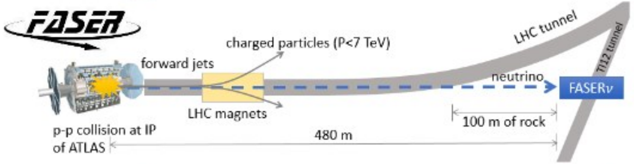
  Δσ ~10% with DsTau reduction of ν_τ beam uncertainty

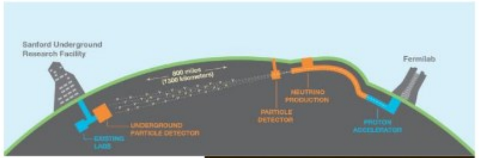
- **FASER**: high energy ν_τ measurements at the LHC

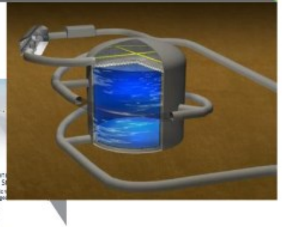
ν_τ cross section has influence to

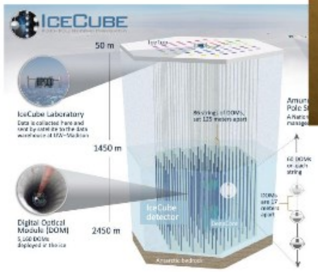
- Long baseline neutrino oscillation experiments
  - **DUNE, Hyper-K, SK**
  - ν_τ is background to ν_e , due to τ→e channel
- **IceCube**
  - Astrophysical ν_τ measurements











ν_τ cross section measurement by oscillated neutrinos

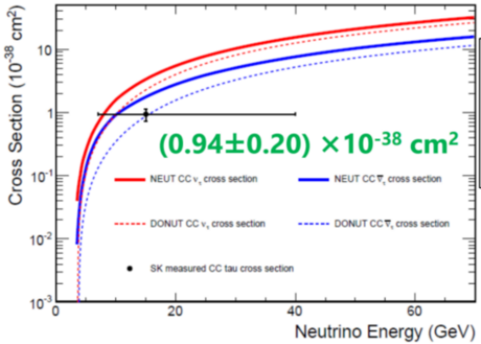
NA65 DsTau

SK

Atmospheric

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

$\sigma_{meas}=(1.47\pm0.32)\ \sigma_{theory}$



arXiv:1711.09436

Presented 1st day by Guillaume Pronost

OPERA

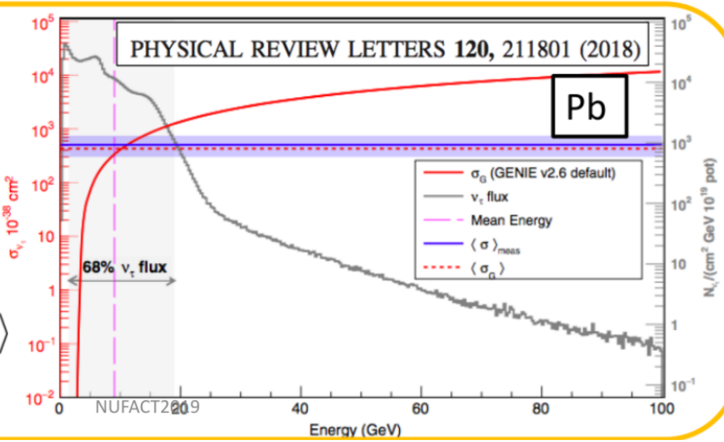
CNGS ν_μ beam

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

σ with a Pb nucleus

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

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

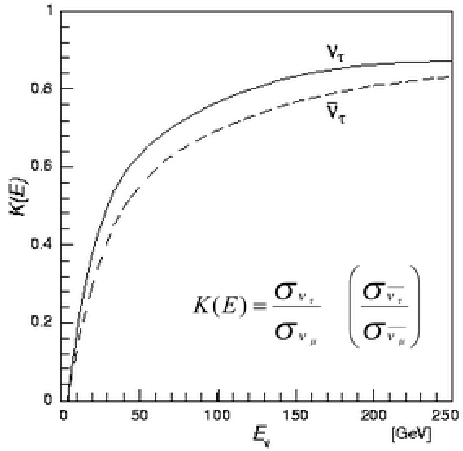


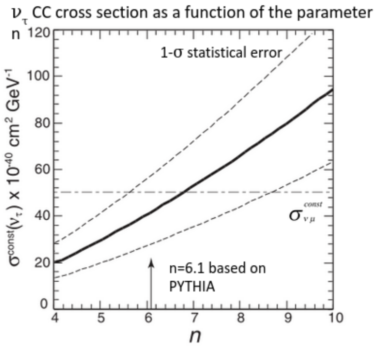
Results from DONuT

NA65 DsTau

$$\sigma_{\nu\tau}(E) = \sigma_{\nu\tau}^{const} \times E_{\nu\tau} \times K_{\tau}(E)$$

ν_τ CC cross section was calculated as a function of one parameter. The energy independent part was parametrizes as





Using PYTHIA-derived value of n=6.1

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

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

where n is the parameter controlling the longitudinal part of the D_S differential cross section

Phenomenological formula

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

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

p_T is transverse momentum

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

Uncertainties in the cross section measurement	DONuT	Systematic uncertainty after DsTau outcome	Future ν_τ measurement with DsTau outcome
ν_τ statistics	0.33		0.02
D_s differential cross section (x_F dependence)	>0.50	0.10	0.10
Charm production cross section	0.17		
Decay branching ratio ($D_s \rightarrow \tau$)	0.23 (0.04 at present)	0.05	0.05
Target atomic mass effects	0.14		

Estimation of parameter n for DONuT re-evaluation

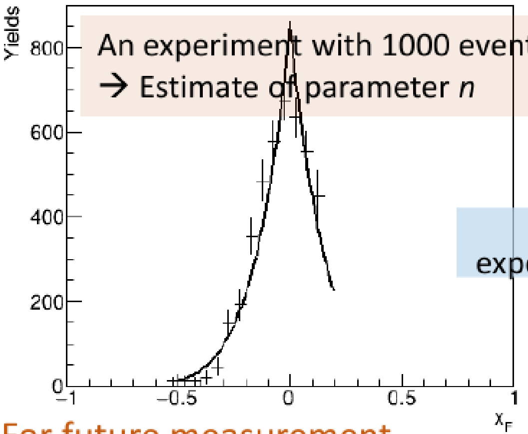
Ds differential cross section

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

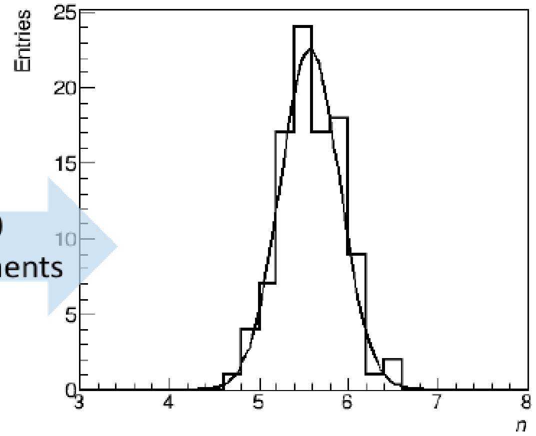
Reconstructed x_F
(corrected by the efficiency)



An experiment with 1000 events
→ Estimate of parameter *n*

100 experiments

Estimated parameter *n*



For future measurement,
a more appropriate parametrization will be used

Unfolding of the reconstruction x_F distribution to be applied (method will be investigated)

Charm production cross section

NA65 DsTau

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		

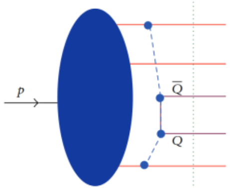
$$\frac{d^2\sigma}{dx_F dp_T^2} \propto (1-|x_F|)^n \exp(-bp_T^2)$$

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

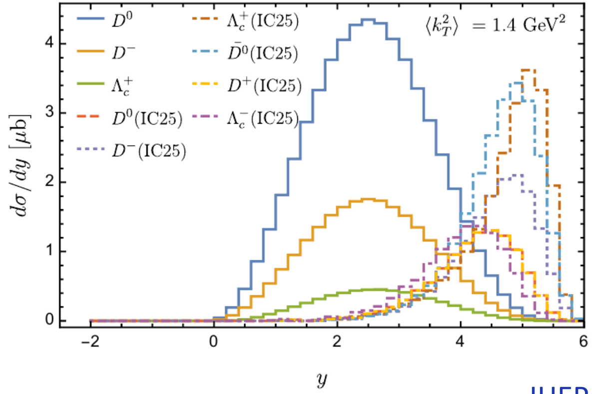
No experimental result effectively constraining the D_s differential cross section at the desired level or consequently the ν_τ production

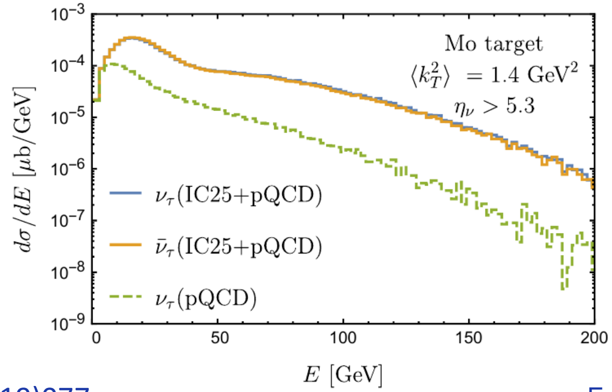
ν_τ production uncertainty

- No experimental data on the D_S differential production cross section in p-N interactions → >50% uncertainty
- Tau neutrino production may be affected by "intrinsic charm" content of proton
  - $c\bar{c}$ quarks which behave like valence quarks
  - Increase charm meson production in forward direction
- ν_τ flux may change by a factor of 10

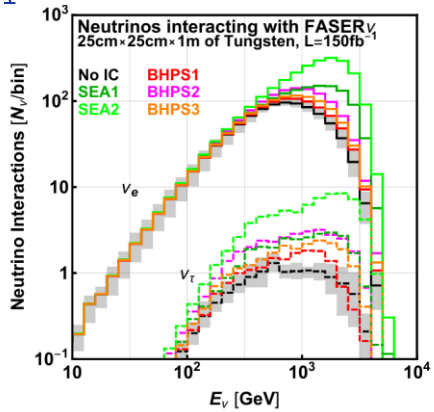


arXiv:1612.01351



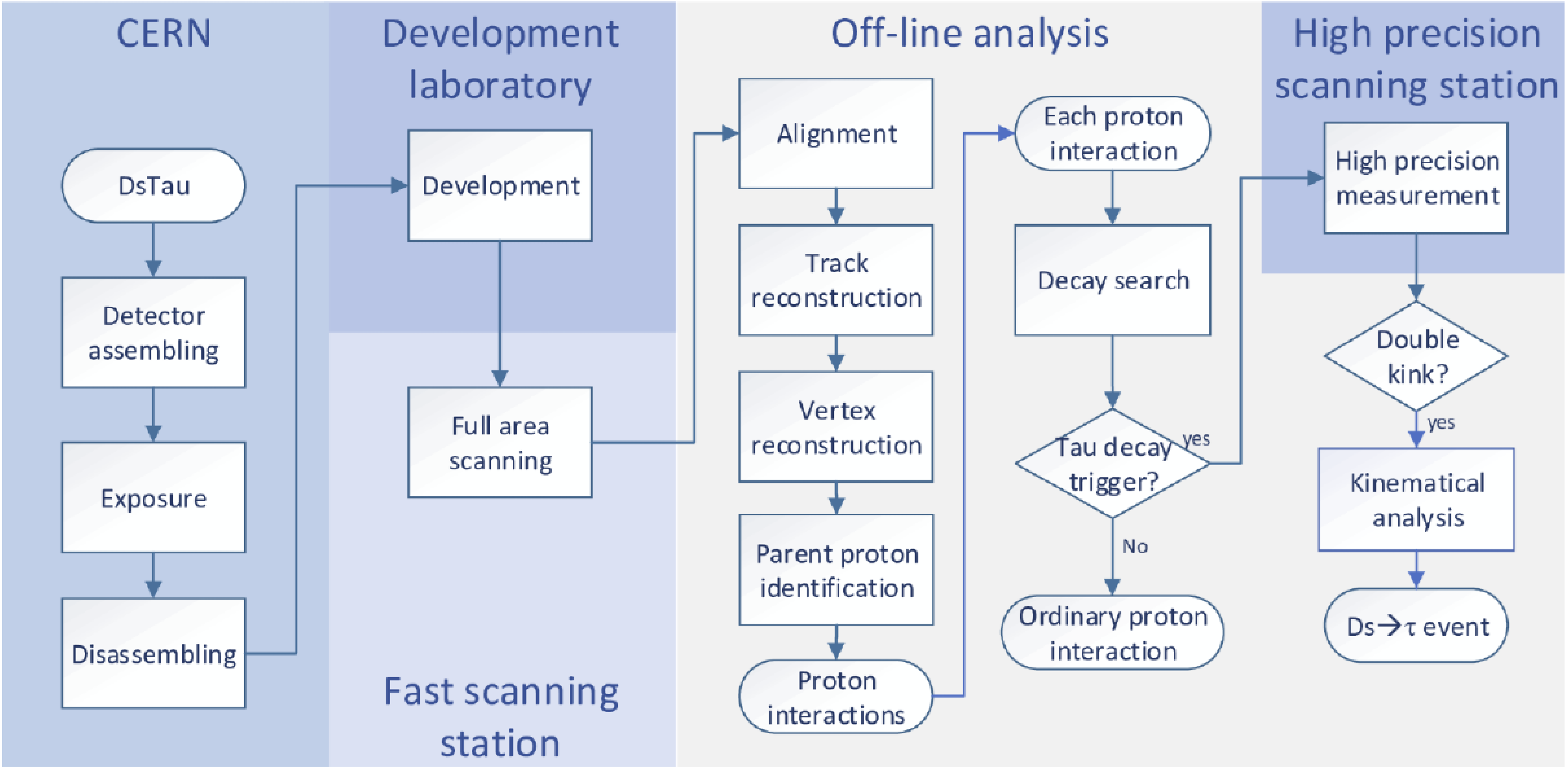


JHEP(2019)077



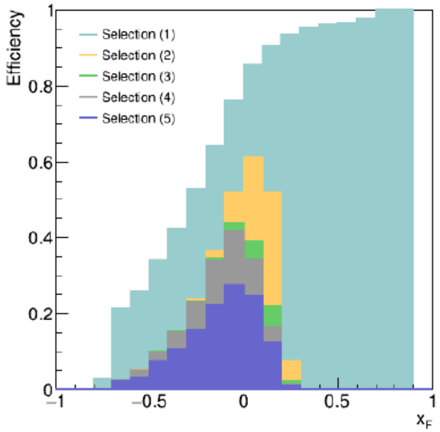
Eur.Phys.J C 80 (2020) 61, arXiv:1908.023

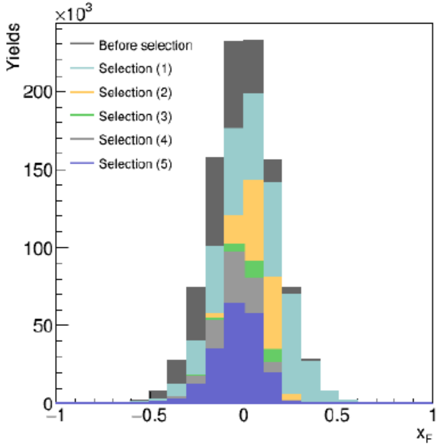
DsTau experiment scheme



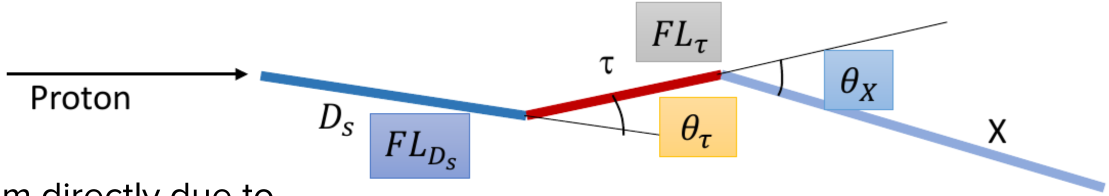
Efficiency for $D_s \rightarrow \tau \rightarrow X$ detection

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

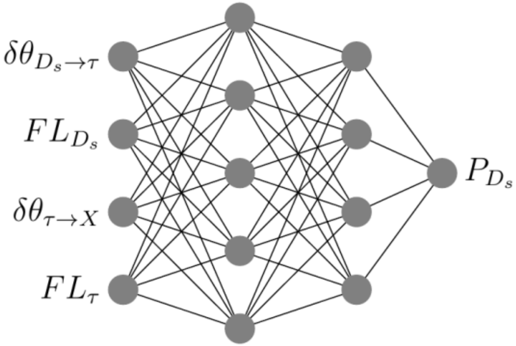


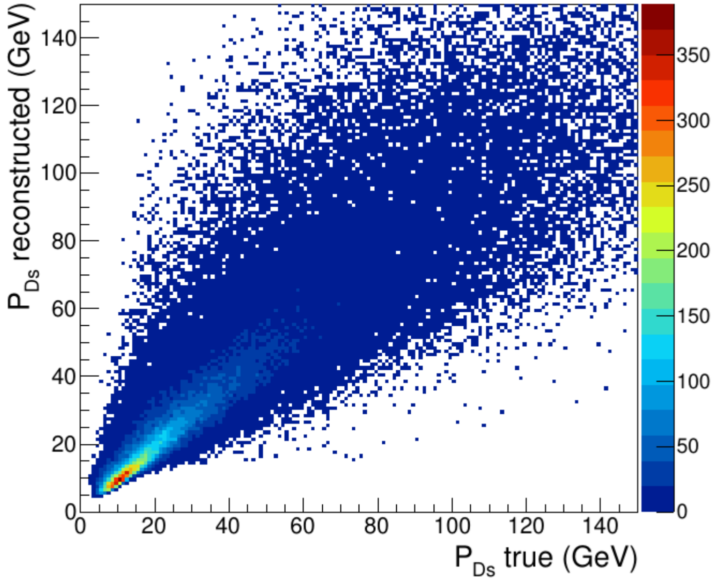


D_s momentum reconstruction



- ➢ It is 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 for τ → 1-prong decay Δp/p = 18%





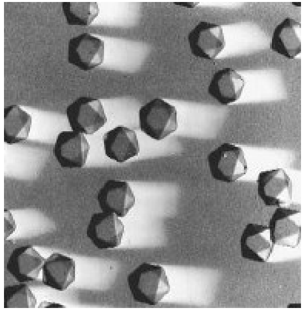
Emulsion detector

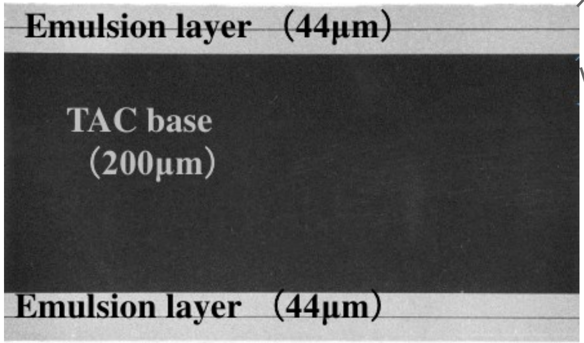
AgBr crystals

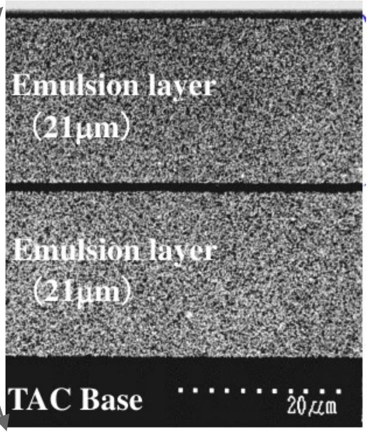
- D = 200 nm
- Detection eff. = 0.16/crystal
- Volume occupancy = 30%

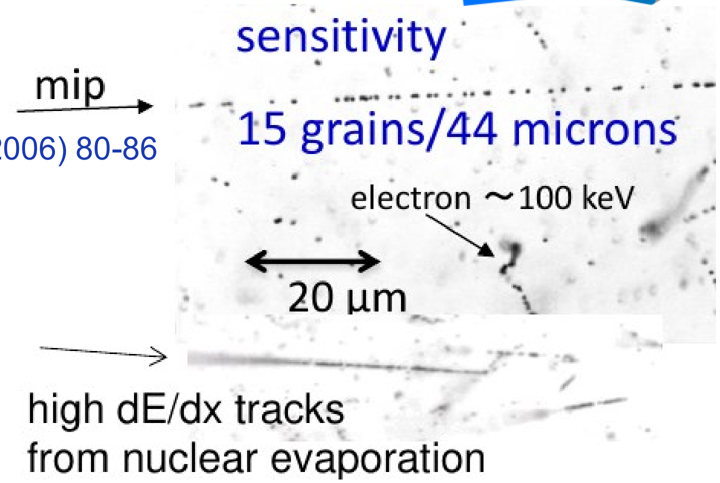
10^{14} crystals in a film

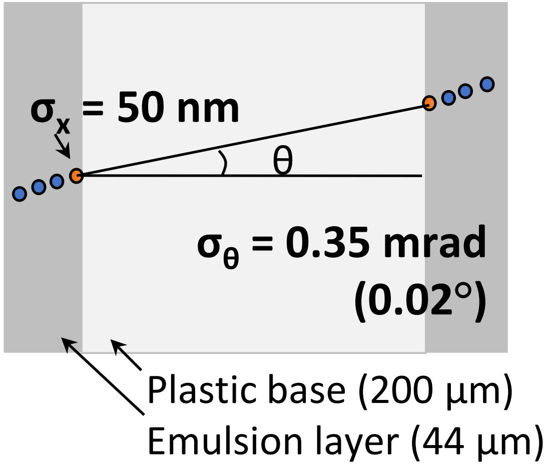
Nucl.Instrum.Meth.A 556 (2006) 80-86







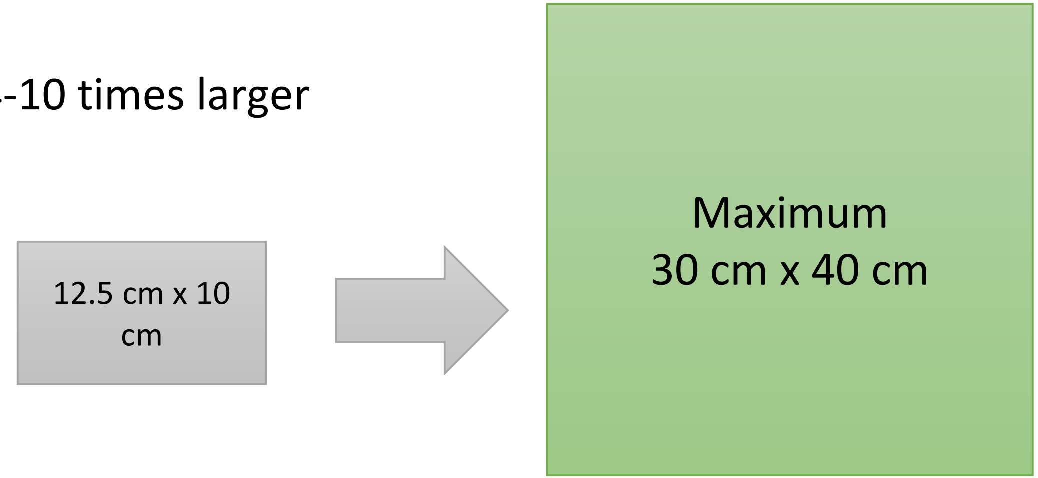




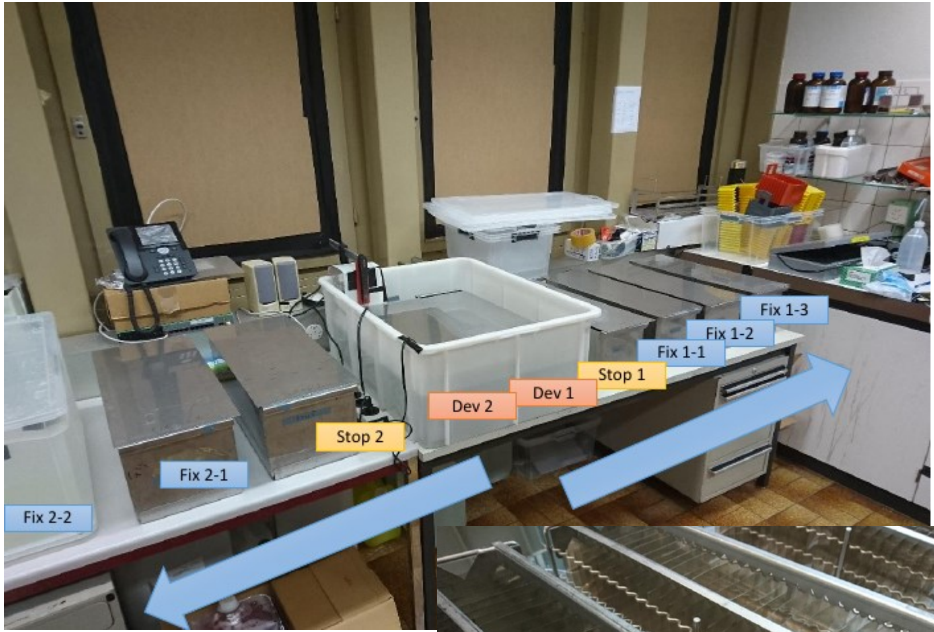
Emulsion film production

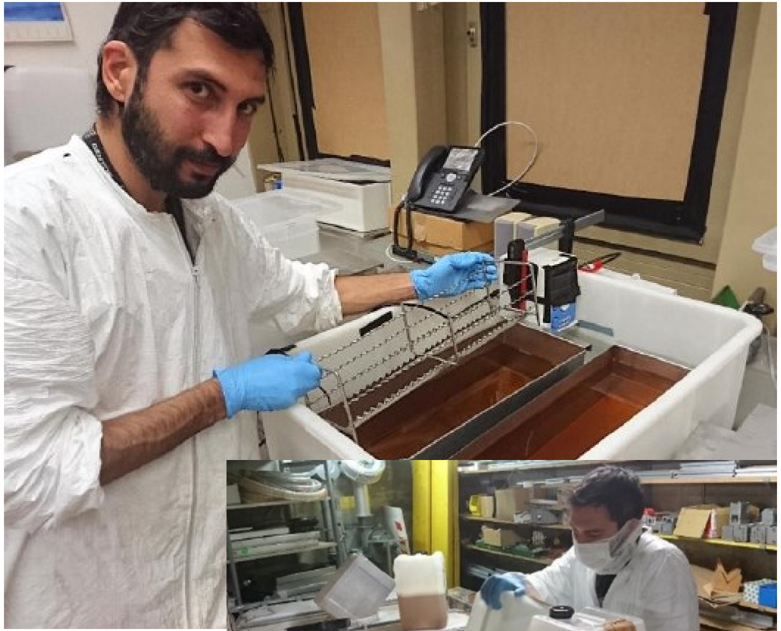
- Gel/Film production in Nagoya University
- Large scale gel production facility is budgeted and under construction.
- Change in film size under discussion to minimize the scanning effort
  - Faster readout with less film exchange
  - No impact to physics performance

4-10 times larger



Emulsion development





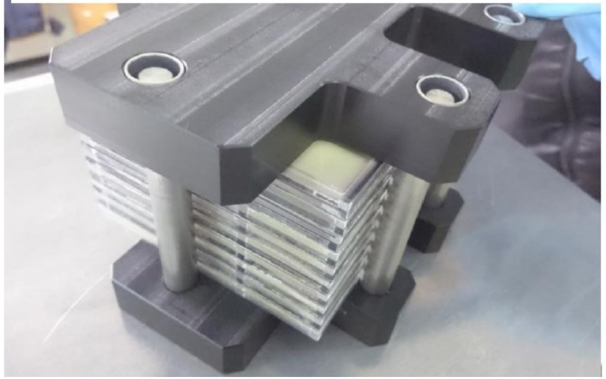
Developed films

4000 12.5 cm x 10 cm films in 2018 pilot run

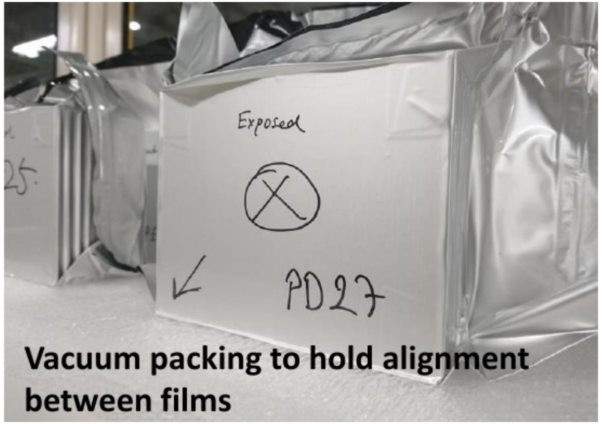
Detector assembling

Pilot run 2018: 30 modules (131 films/module, 235 components) prepared i n total

Mechanical support to assemble modules



A module under assembling in dark

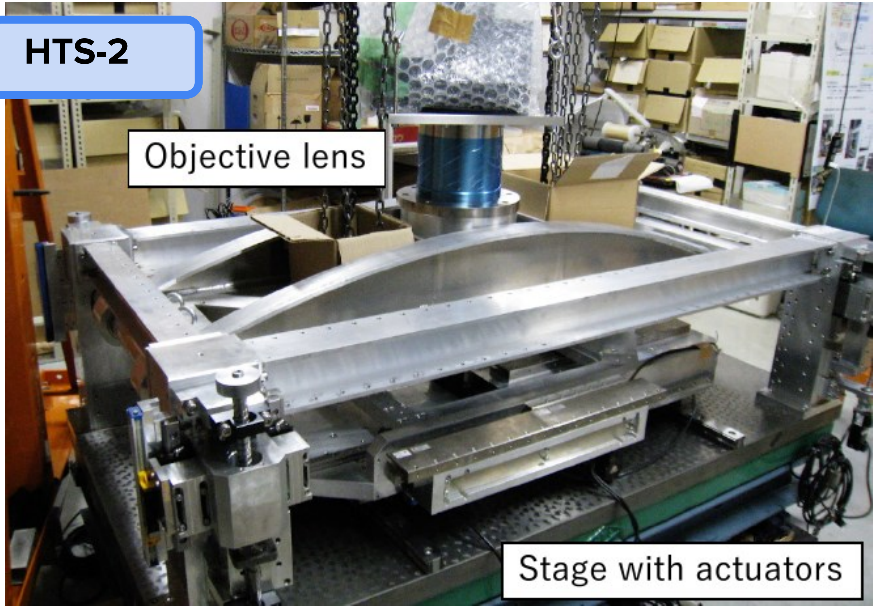


Vacuum packing to hold alignment between films

A module on the target mover

New scanning system preparation

NA65 DsTau

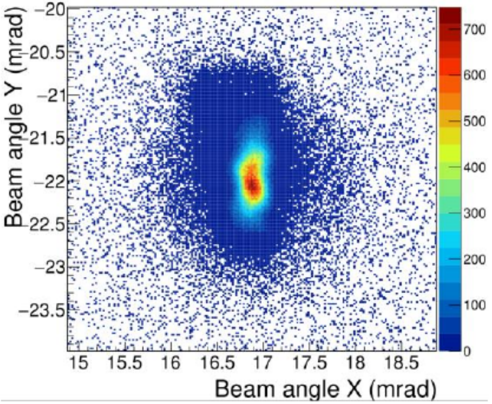


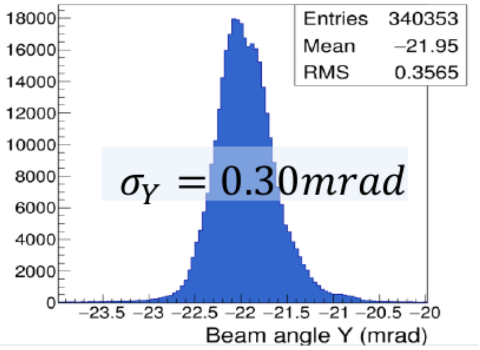
- Scanning speed of HTS-1 will be achieved by the end of 2020
- Scanning speed of 25000 cm^2/h/layer will be achieved in 2021
- Readout time necessary for each physics run will be less than 1 year (including the detector optimisation)

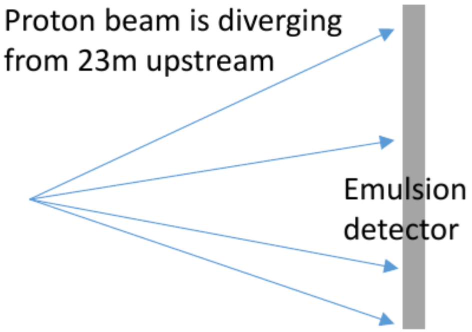
	S-UTS (OPERA)	HTS-1	HTS-2 under construction
Readout speed [cm^2/h/layer]	72	4700	25000
Field of view [mm^2]	0.052	25	50
Readable area [m^2]	0.0125	0.0125	0.1
Drive mode	Continuous	Step by step	Continuous

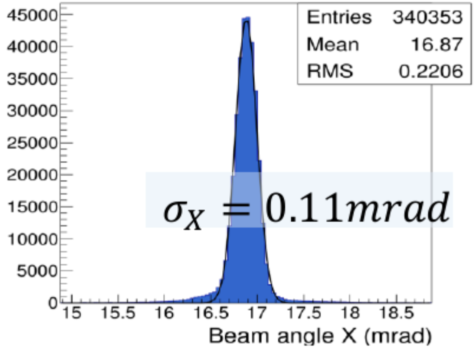
Proton beam angle structure

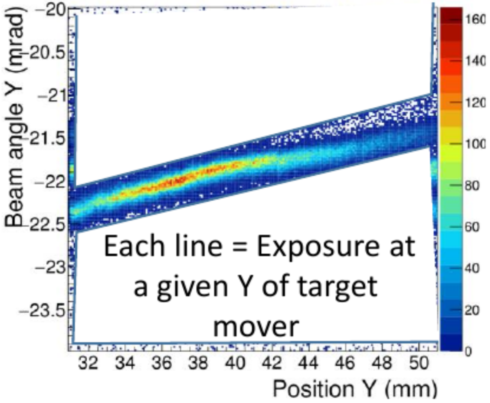
- Proton beam tracks were checked in detail
    - Tracks reconstructed in 20 emulsion films, thickness of 1.1 cm

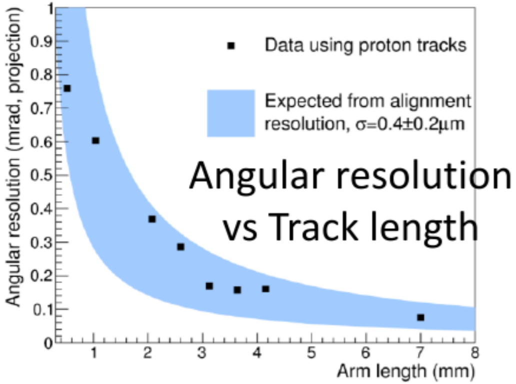










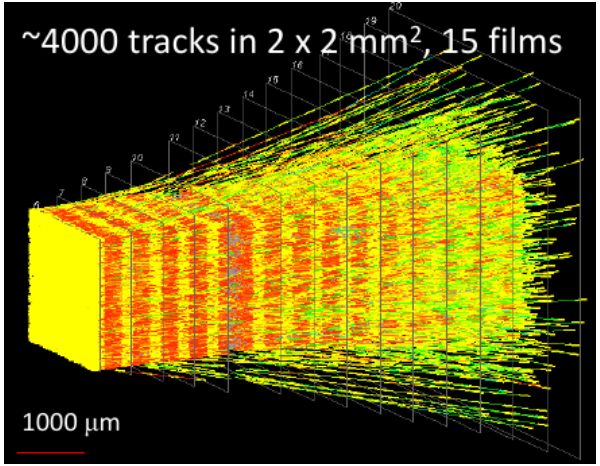


Reconstruction of proton interactions

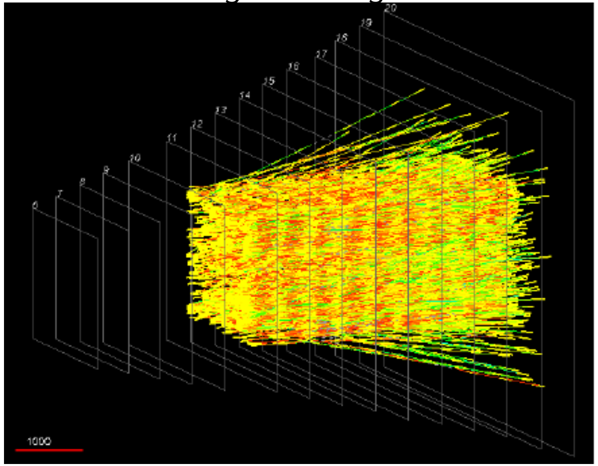
NA65 DsTau

- Microscope data taking
  - Pixel size = 0.3 µm x 0.3 µm x 2 µm
- Data size
  - ~10 TB image data/film (125 cm^2)
  - ~50 PB was processed in the 2018 pilot run (50 m^2)
  - 10 GB/film after compression to be stored
- Track density
  - OPERA: 100 tracks/cm^2 in wide angular space (θ<500 mrad)
  - DsTau: 100,000 tracks/cm^2 in wide angular space (θ<10 mrad)

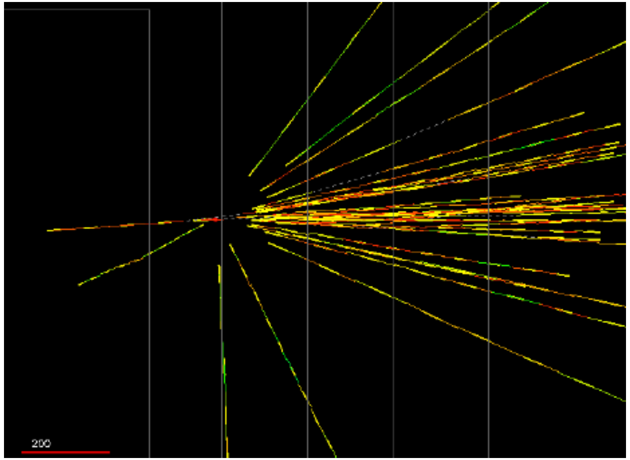
Reconstructed tracks



Tracks starting after tungsten

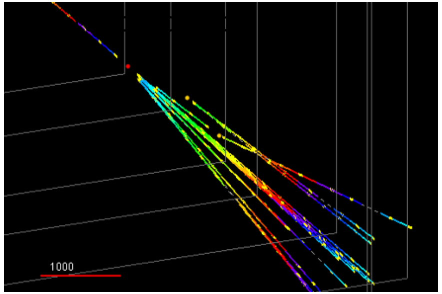


Vertex reconstruction

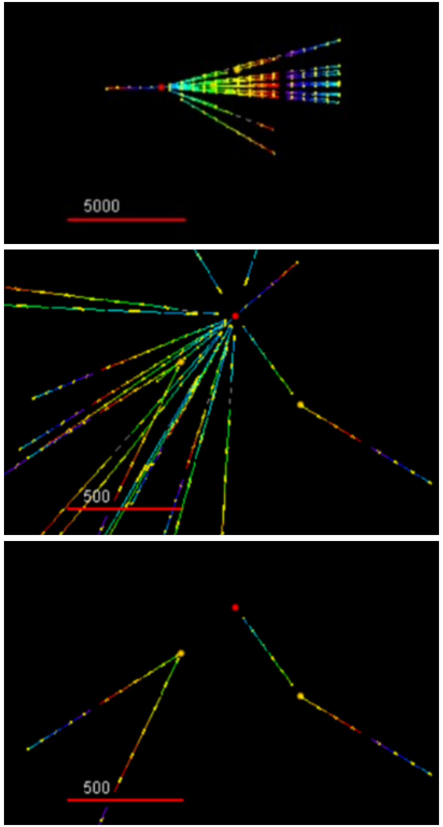


Event display

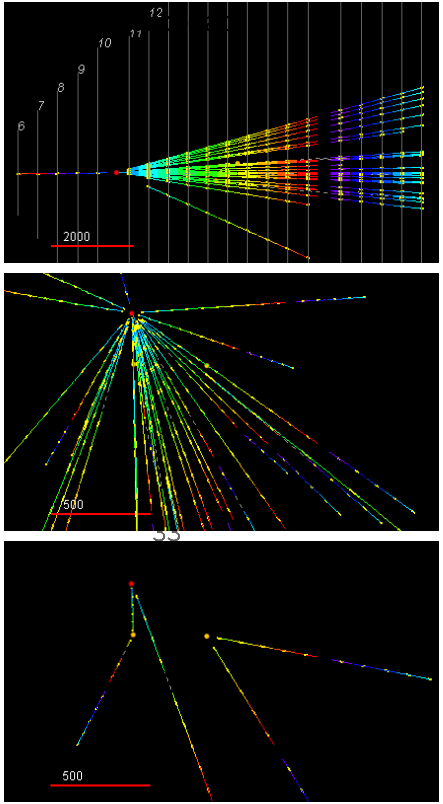
cand_20190117_p11_7165
1.2_33380.6



cand_20181205_p11_4729
1.8_32047.5

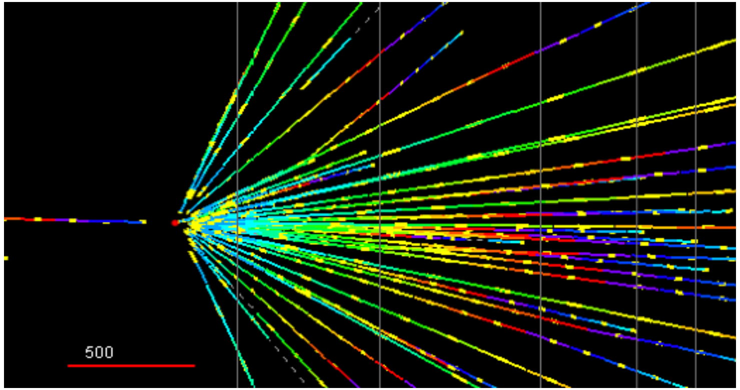


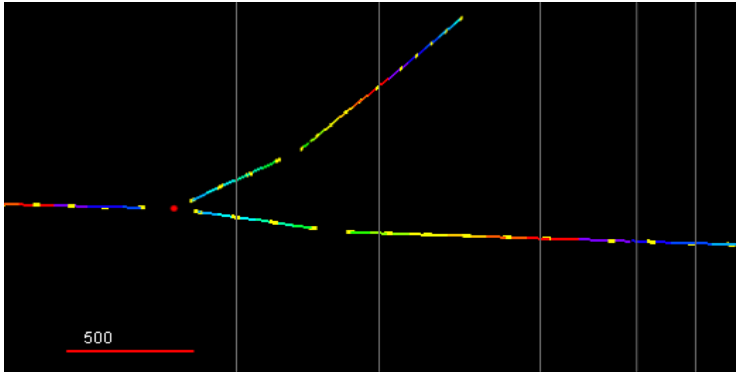
cand_20181205_p11_7218
2.0_63924.7



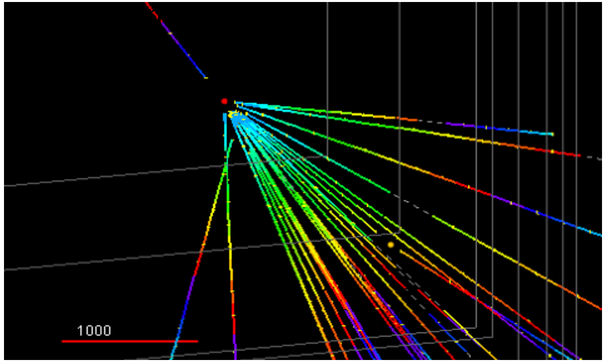
Event display

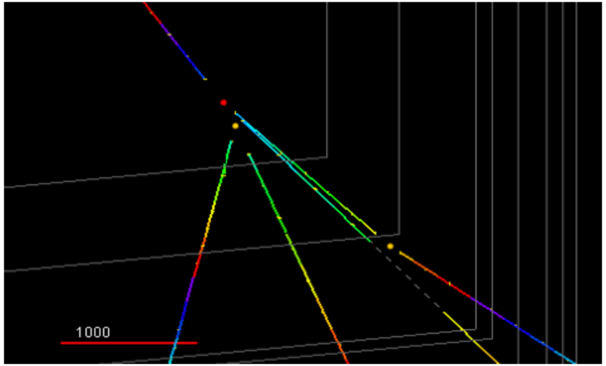
cand_20190117_p11_61598.3_476
32.7





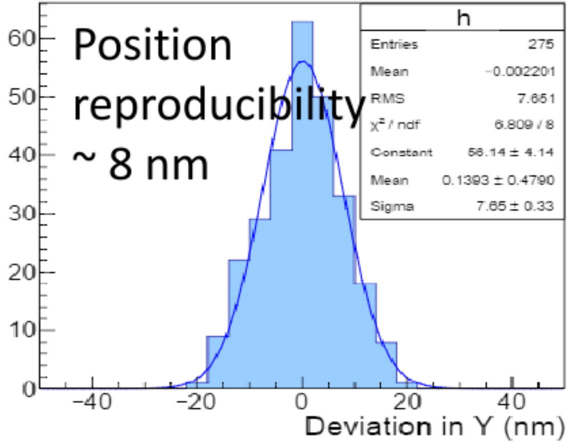
cand_20190117_p11_61427.6_56
633.2

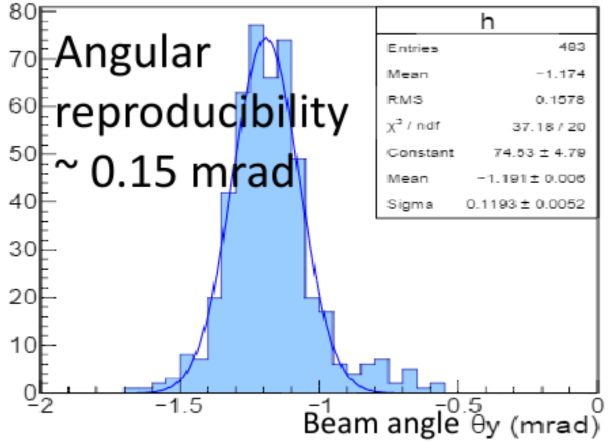


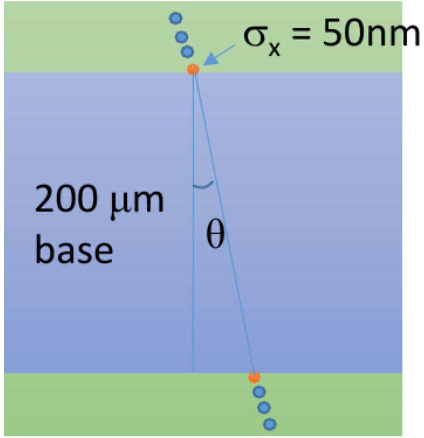


High precision measurement of track angles

- Intrinsic resolution of each grain = 50 nm
  - Two grains on top and bottom of 200 μm base → 0.35 mrad
  - Discrimination of 2 mrad at 4σ level
- A high precision system with a Piezo-based Z axis developmented



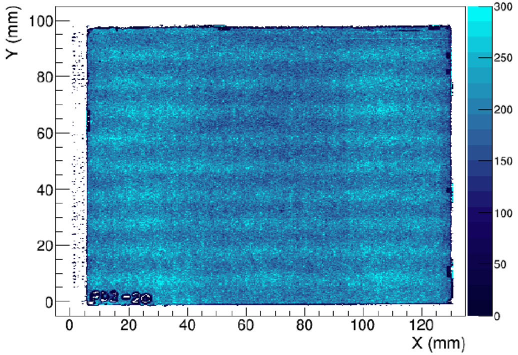




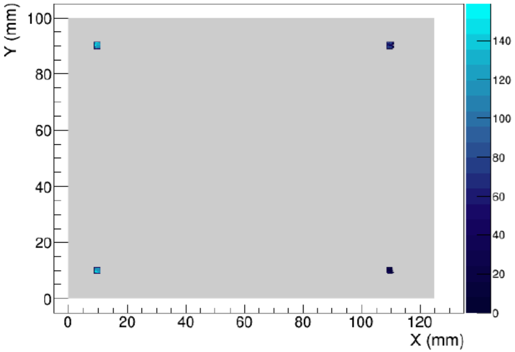
Piezo objective scanner

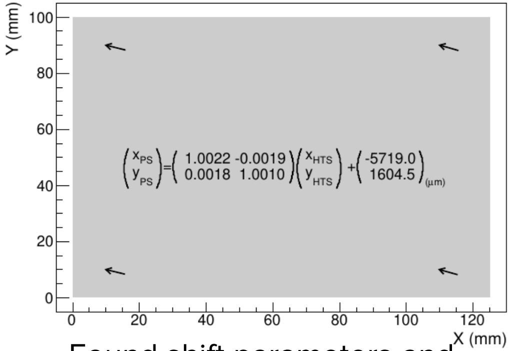
Alignment between HTS and piezo-based microscope

Position distribution of the HTS data

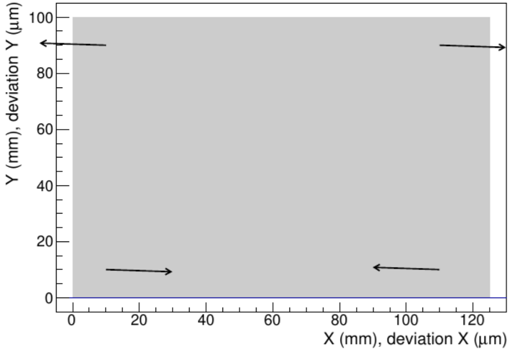


PS data for alignment





Found shift parameters and calculated affine parameters



Residual from the affine transformation