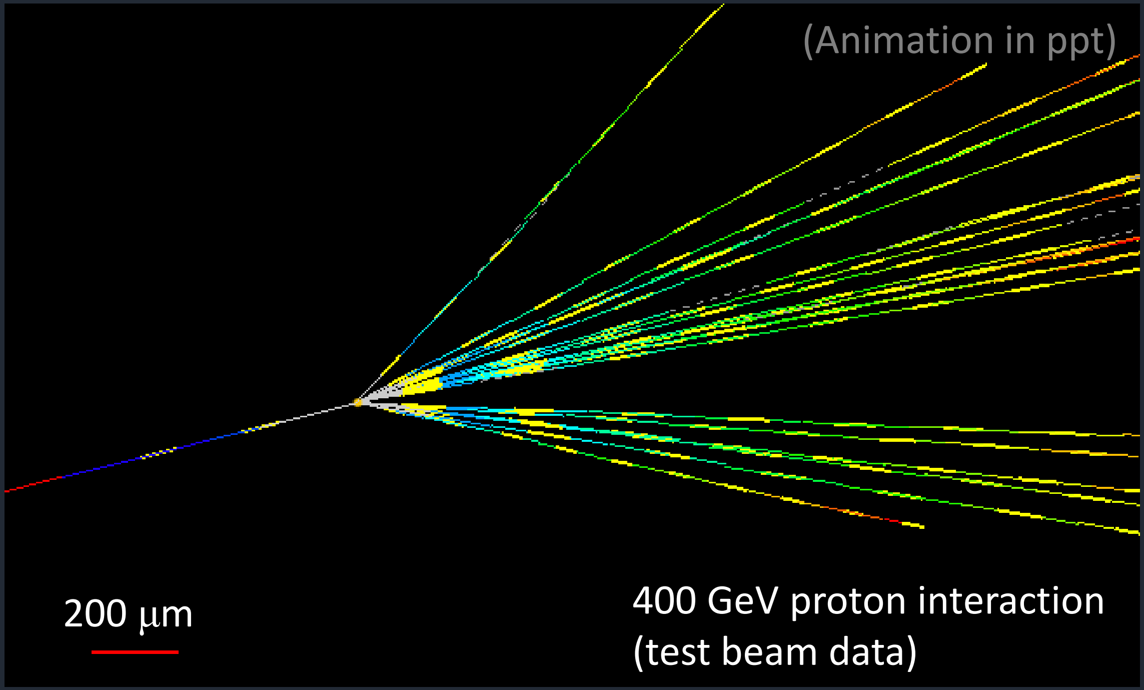
Proposal to study tau-neutrino production in high-energy proton interactions (SPSC-P-354)

Tomoko Ariga for the DsTau collaboration

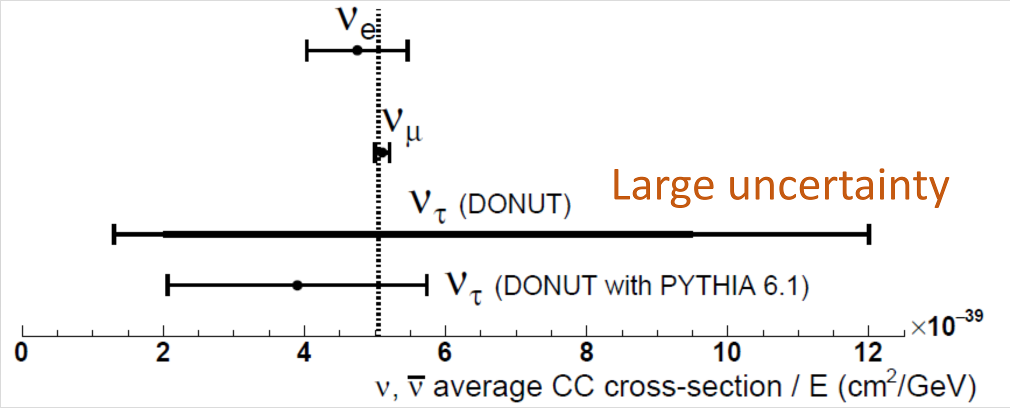
Kyushu University & University of Bern



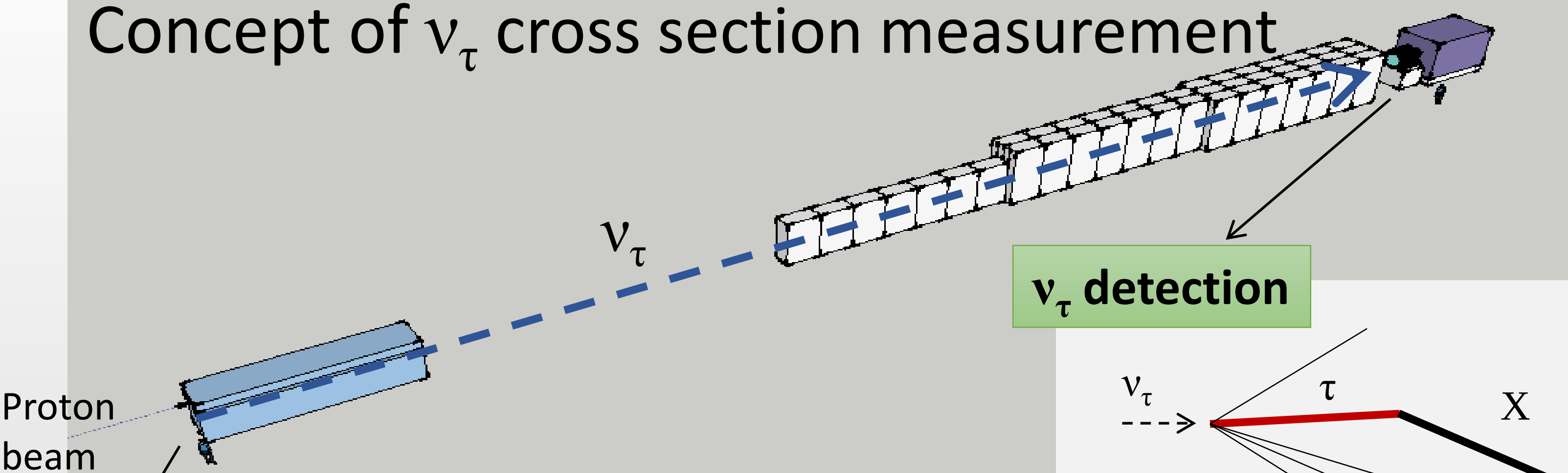
Physics motivations

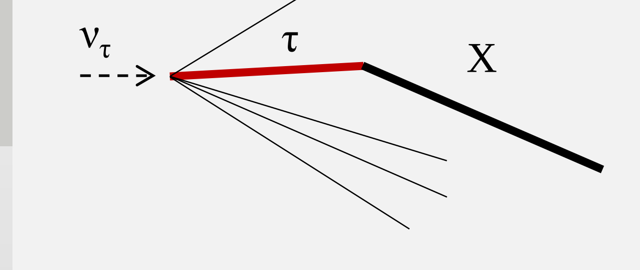
- Tau neutrinos are among the less known particles in the SM
- Large systematic uncertainty in the cross section measurement

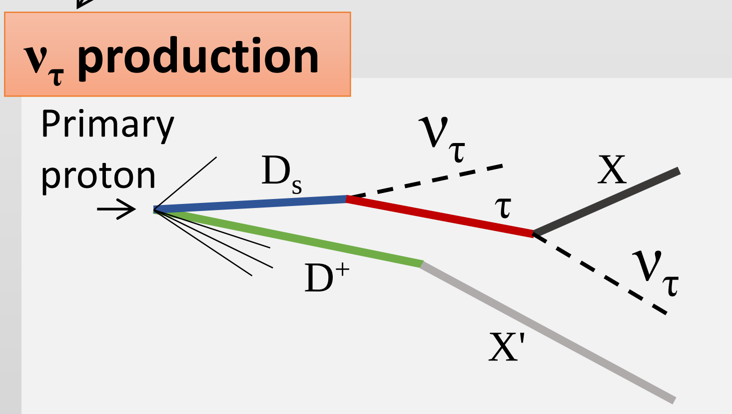
- Precise measurement of ν_τ CC cross section would be:
  - Search for new physics effect in ν_τ – nucleon interaction
  - Important for future neutrino experiments and astrophysical ν_τ observations



Concept of ν_τ cross section measurement







ν_τ detection:

- **Statistical uncertainty 33% in DONUT** (first observation of ν_τ interactions, total 9 events)
- **~2% in future experiments**

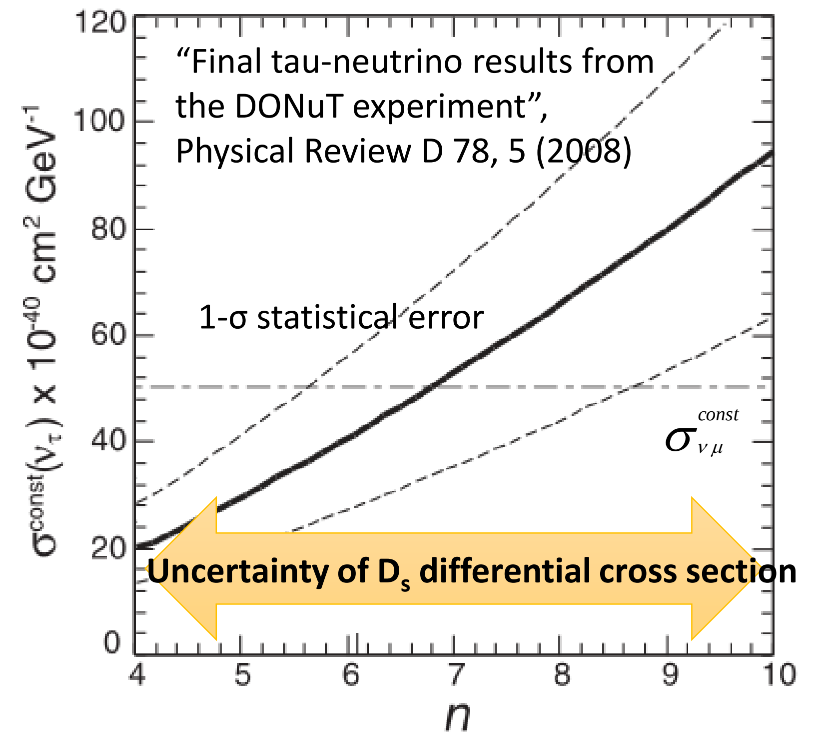
Main ν_τ source: $D_s \rightarrow \tau$ decays produced in proton interactions
→ No experimental data on differential cross section of D_s
→ **Large systematic uncertainty (~50%)** in the ν_τ flux prediction

Systematic uncertainty in DONuT measurement

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

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

Parameter-dependent cross section result



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

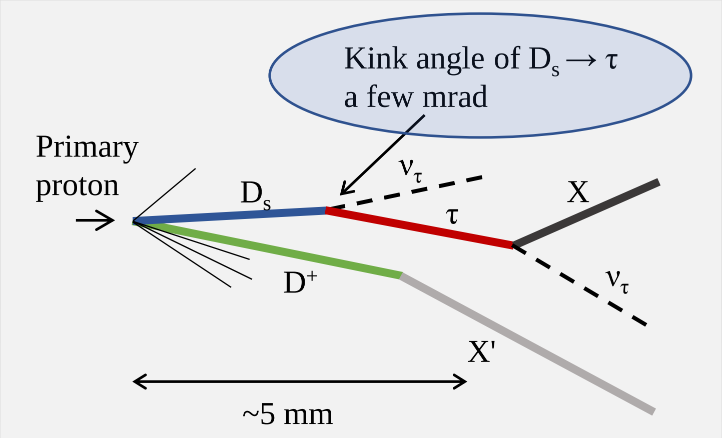
The energy-independent part was parameterized as

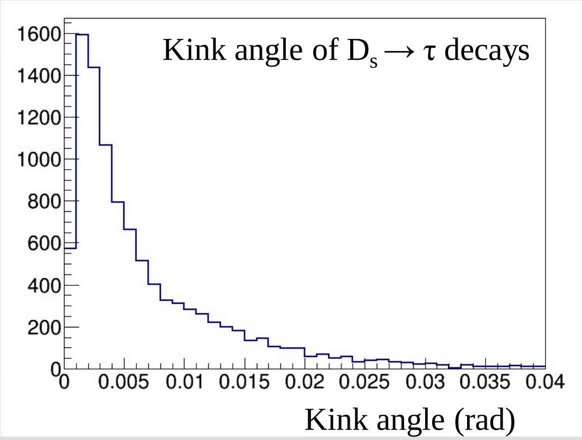
$$\sigma_{\nu\tau}^{const} = 7.5(0.335\, n^{1.52}) \times 10^{-40}\, cm^2 GeV^{-1}$$

The DsTau project at the CERN SPS

- **Goals**
  - Measurement of ν_τ production
  - Reduce systematic uncertainty in the cross section measurement 50% → 10%
    - Re-evaluation of the DONUT result
    - Important input for future ν_τ experiment: ν_τ program in SHiP

- **Principle of the experiment**
  - Detect double-kink + another decay topology within a few mm
    - Technical challenge to detect small kink angle of $D_s \to \tau$ decays
  - Measure D_s differential production cross section





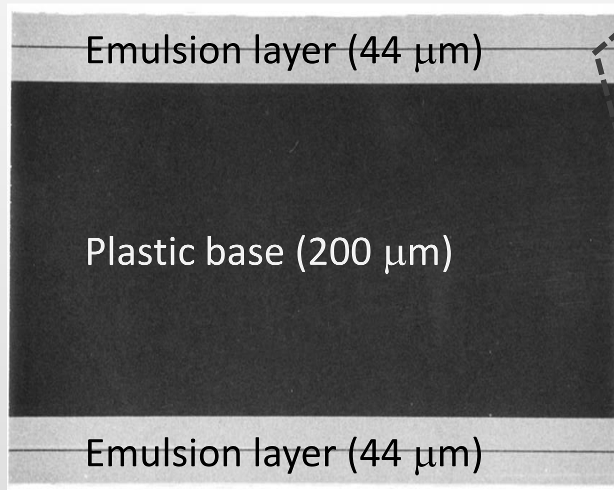
Emulsion detectors:
3D tracking device with 50 nm precision

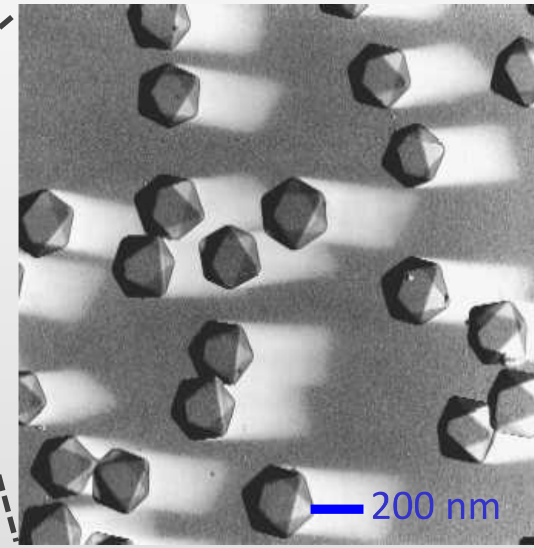
AgBr crystal

10^{14} crystals in a film

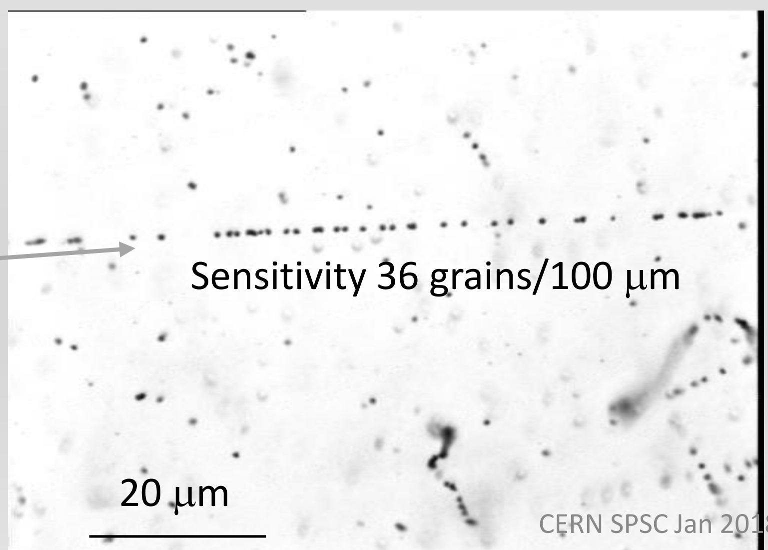
Emulsion film

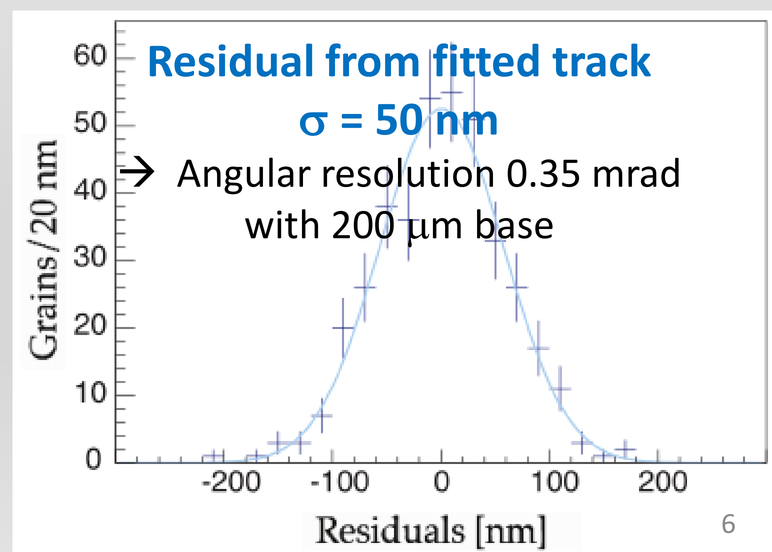
Cross-sectional view





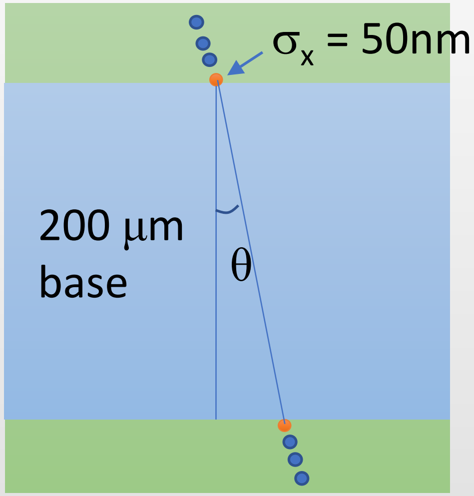
10 GeV/c π beam

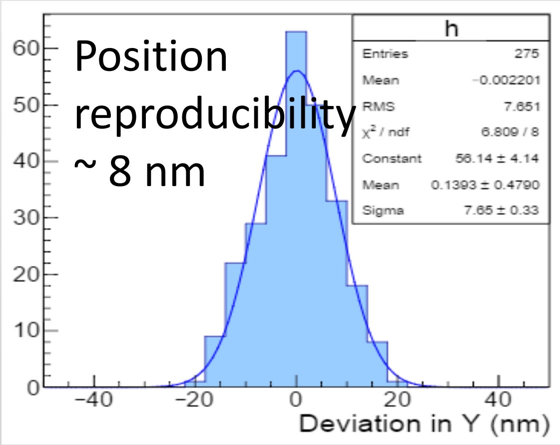


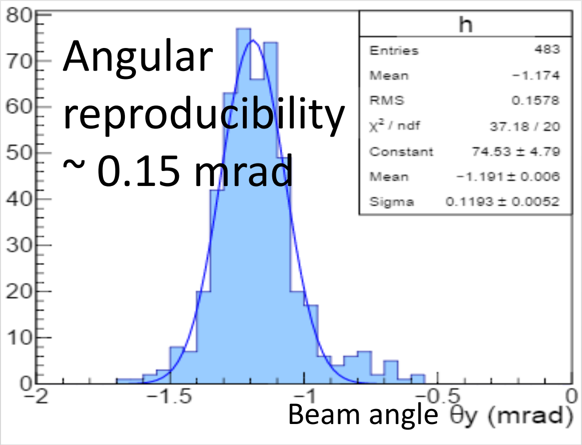


High precision measurement of track angles

- 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 new system with piezo-based Z axis under development
- Angular measurement reproducibility of 0.15 mrad was achieved



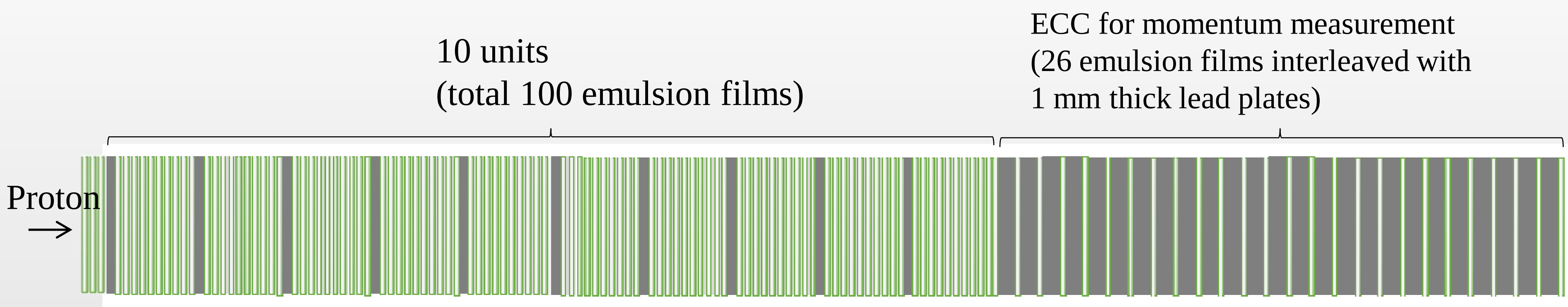


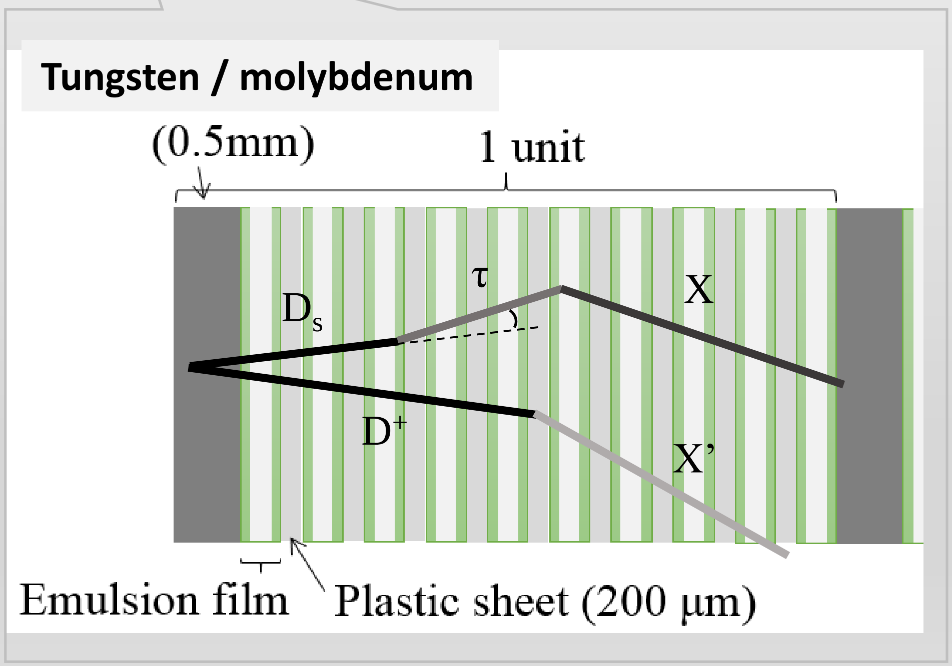


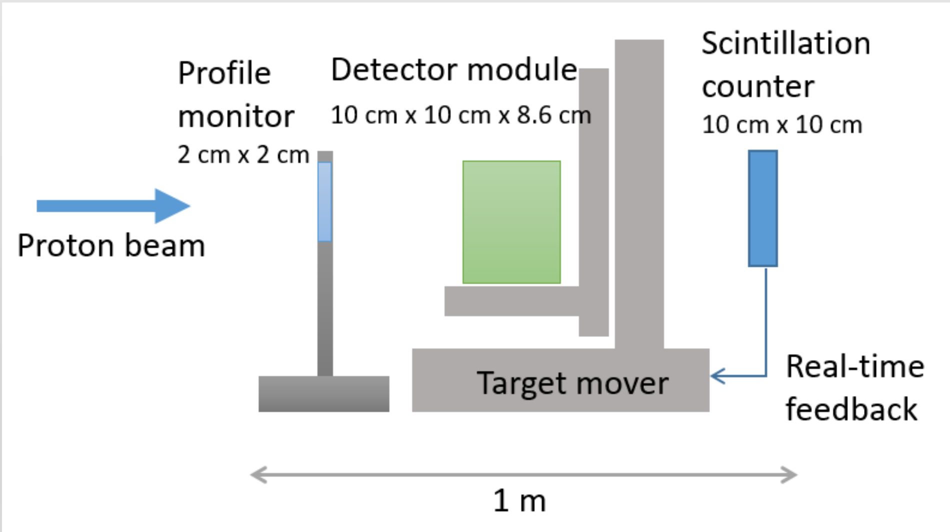
Piezo objective scanner

- Angular alignment between films to be done by using dense 400 GeV proton tracks

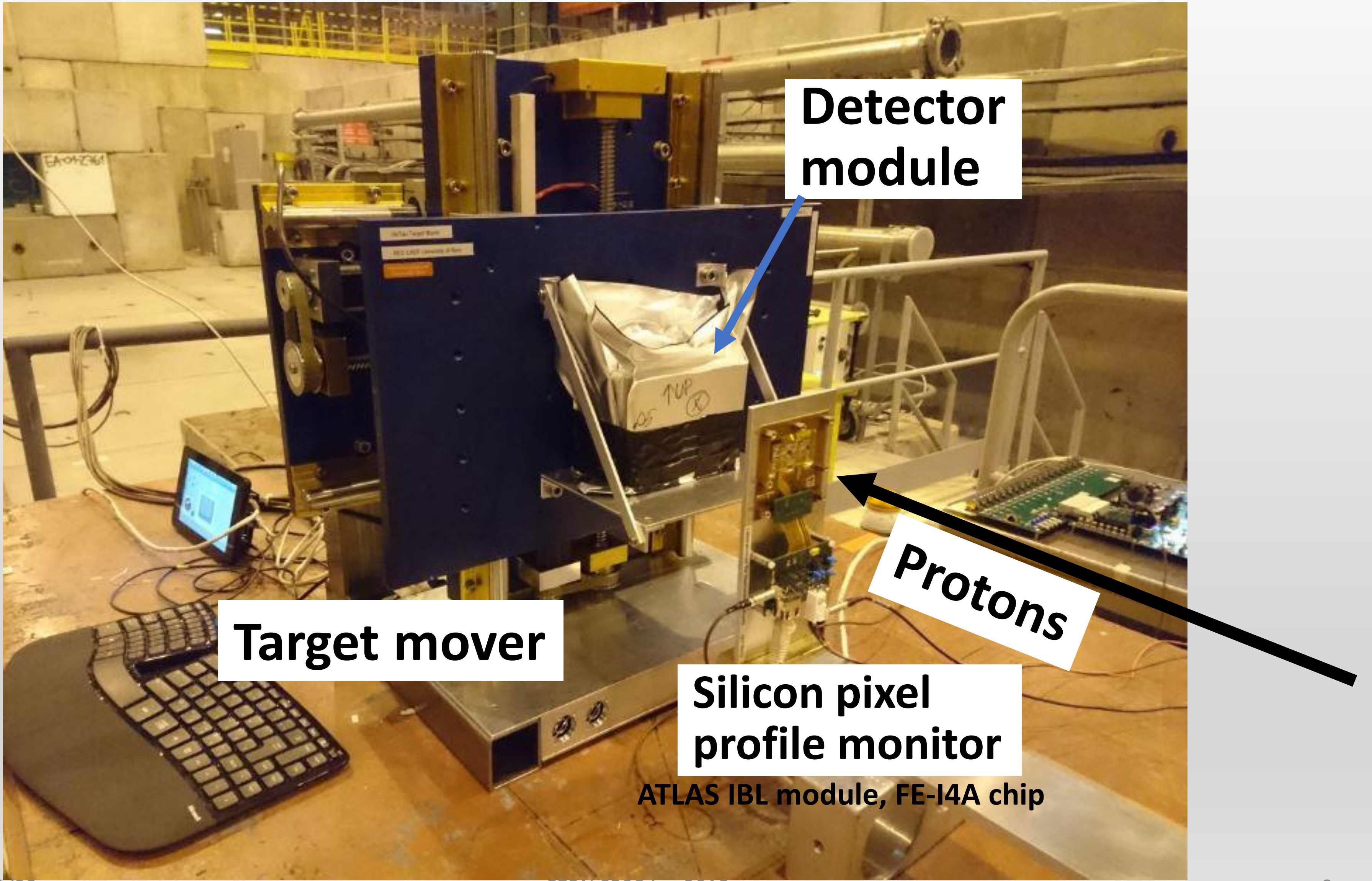
Module structure for $D_s \rightarrow \tau \rightarrow X$ measurement





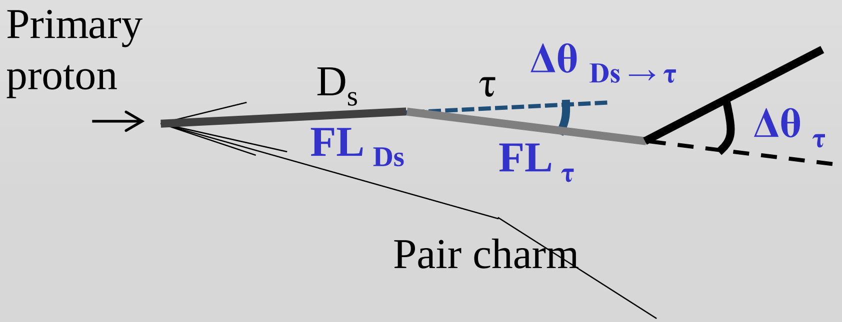


Experimental setup at the H4 beamline (beam test)



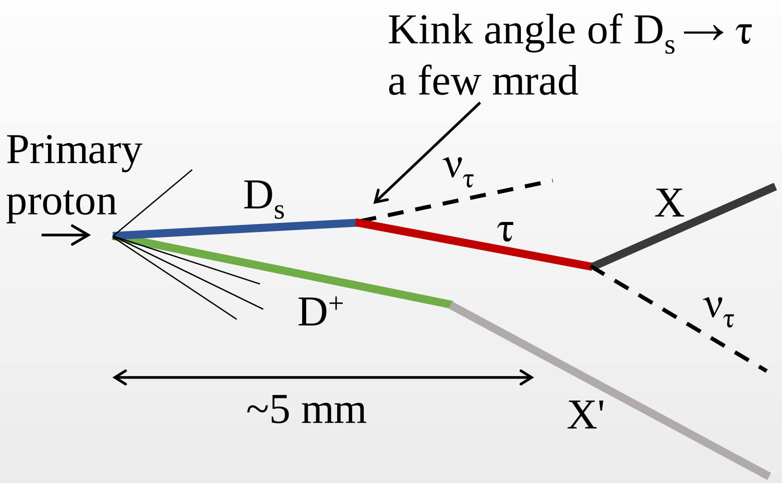
Efficiency of $D_s \rightarrow \tau \rightarrow X$ detection

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



FL: flight length
Δθ: kink angle

Expected signal events



- Design values

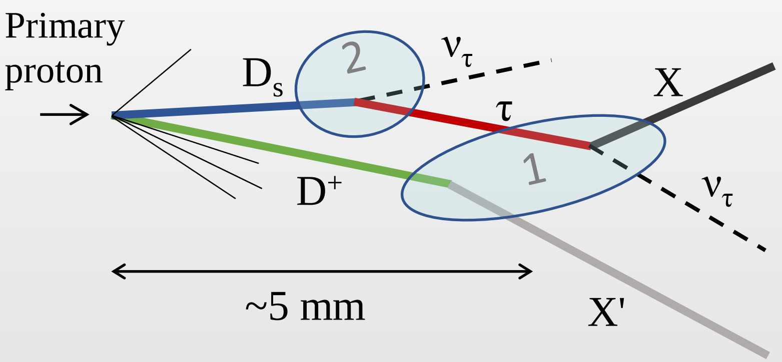
Analysis of 2.3x10^8 proton interactions with 4.6x10^9 pot

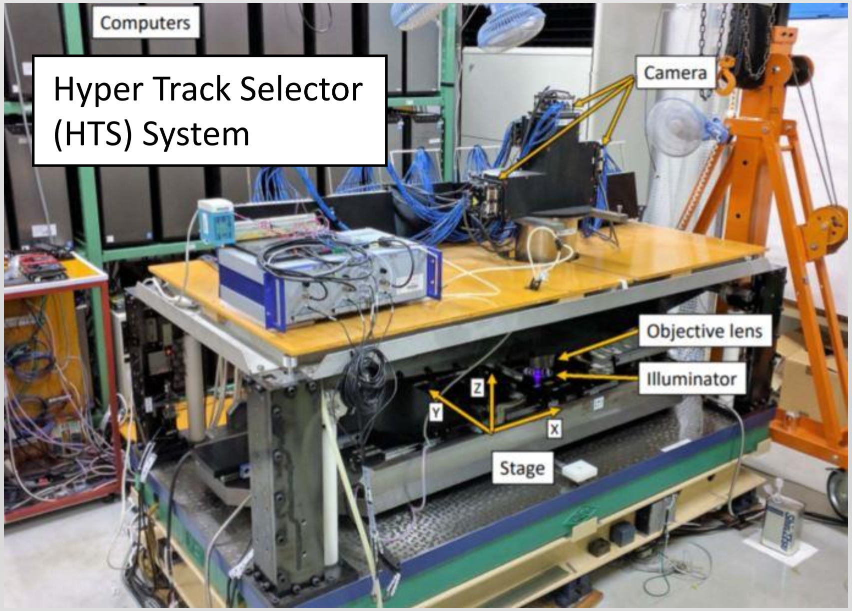
4x10^5 charm-pairs produced
9x10^4 D_s produced
5000 $D_s \to \tau$ events produced → **1000 $D_s \to \tau$ events will be detected**

- With beam density 10^5 /cm^2, detector surface of 4.6 m^2 (film surface 593 m^2) to be scanned

Two step analysis for double kink search

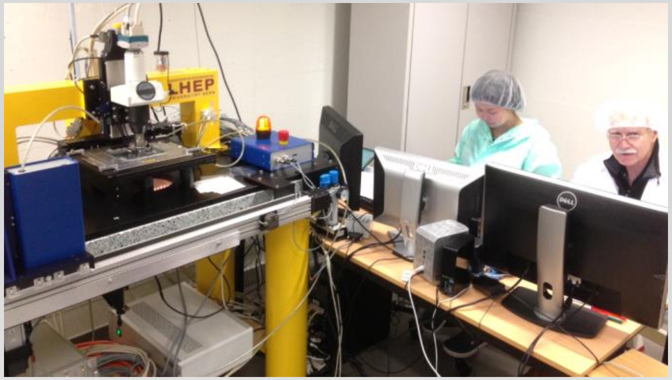
1. High speed scanning of full area
   to select $\tau \rightarrow X$ + partner-charm decays
   ($\Delta\theta$ ~100 mrad)
2. Precision measurement
   to detect $D_s \rightarrow \tau$ decay (a few mrad)





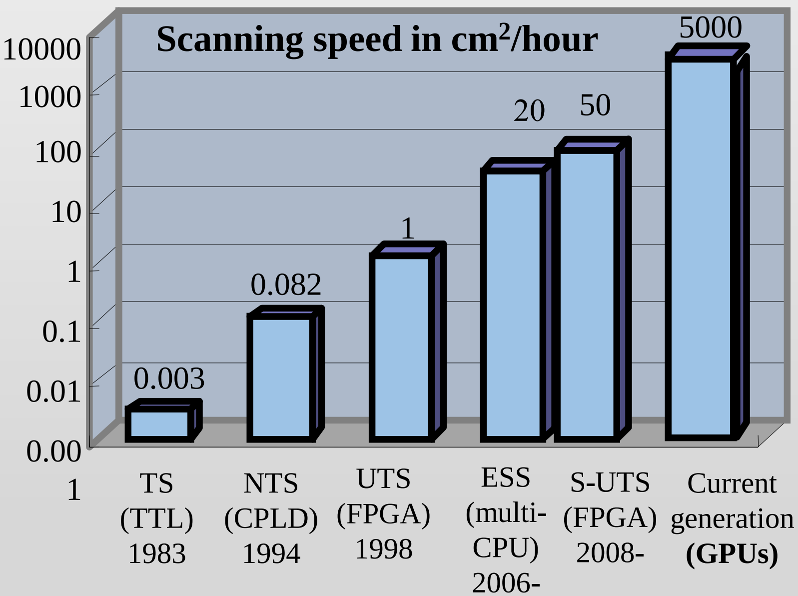
A fast scanning system in Nagoya
Scanning speed 0.5 m²/h/layer
Angular resolution ~2 mrad

Nano-precision measurements in Bern
Angular resolution ~0.3 mrad



Evolution of automated scanning system

Development of scanning system started in 1970s.



FOV 5x5 mm^2

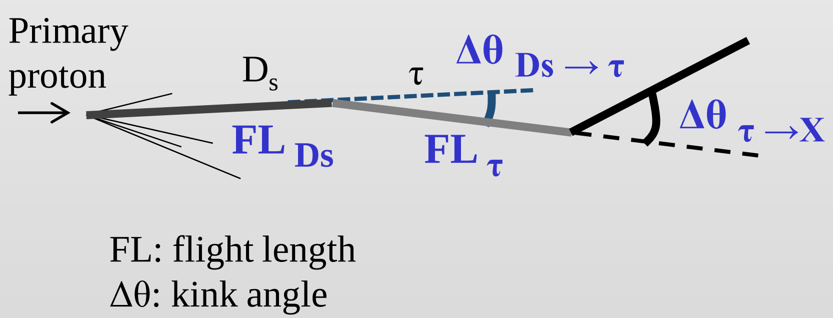
Scanning speed 0.5 m^2/h

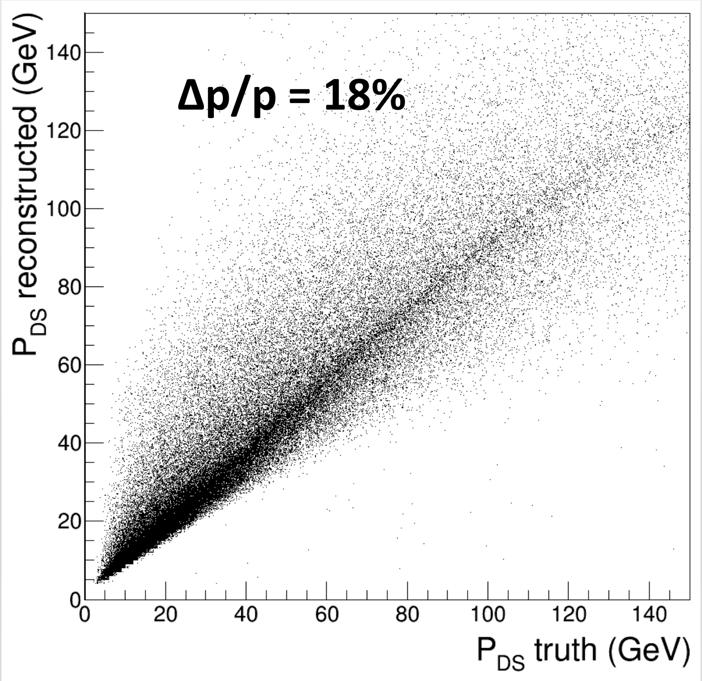
100 times faster than OPERA

D_s momentum reconstruction

- Difficult to measure D_s momentum directly due to short lifetime

→ New method for D_s momentum reconstruction by topological variables





- A Neural Network with 4 variables was trained with MC events
- Momentum resolution for $\tau \to 1$ prong decays $\Delta p/p$ = 18%

Expected performance

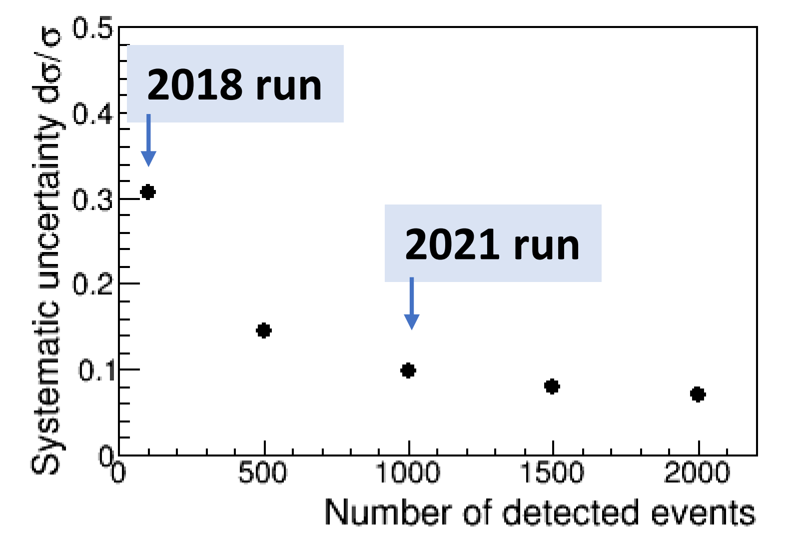
Relative systematic uncertainty for cross section measurement:

~30% with 2018 run

→ Re-evaluation of the DONUT result

~10% with 2021-2022 run

→ Input for future measurement

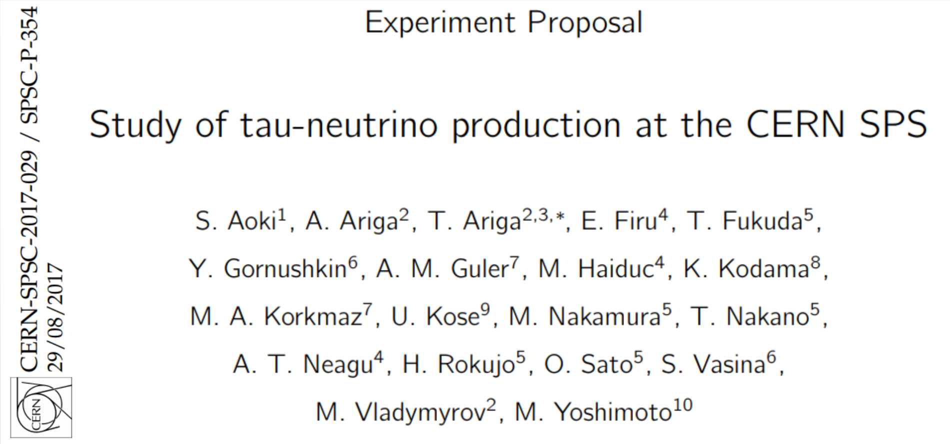


Uncertainties in cross section measurement	DONuT	Systematic uncertainty after DsTau outcome	Future ν_τ measurement with DsTau outcome
ν_τ statistics	0.33		0.02
D_s differential cross section (x_F dependence)	>0.50	0.10	0.10
Charm production cross section	0.17		
Decay branching ratio ($D_s \rightarrow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

Aiming at 10% precision to look for new physics effects in ν_τ -nucleon CC interactions

Status of the project

- Letter of Intent, Feb. 2016
  - Beam tests in Nov. 2016, May 2017
- Proposal (SPSC-P-354), Aug. 2017


CERN-SPSC-2017-029 / SPSC-P-354
29/08/2017

Experiment Proposal

Study of tau-neutrino production at the CERN SPS

S. Aoki[1], A. Ariga[2], T. Ariga[2,3,*], E. Firu[4], T. Fukuda[5], Y. Gornushkin[6], A. M. Guler[7], M. Haiduc[4], K. Kodama[8], M. A. Korkmaz[7], U. Kose[9], M. Nakamura[5], T. Nakano[5], A. T. Neagu[4], H. Rokujo[5], O. Sato[5], S. Vasina[6], M. Vladymyrov[2], M. Yoshimoto[10]

- The DsTau collaboration
  - The collaborators are experienced scientists from the former CHORUS, DONUT, OPERA and cosmic-ray experiments. Some are also involved in the SHiP project.

Japan:	Switzerland:	Romania:	Russia:	Turkey:
Nagoya	Bern	Bucharest	Dubna	Ankara
Kyusyu				
Aichi				
Kobe				

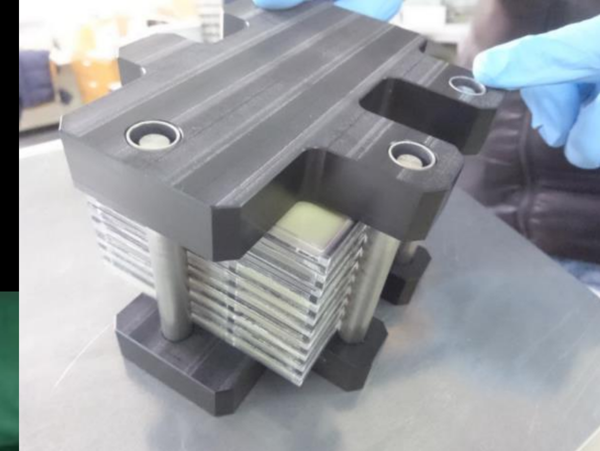
Run plan and schedule

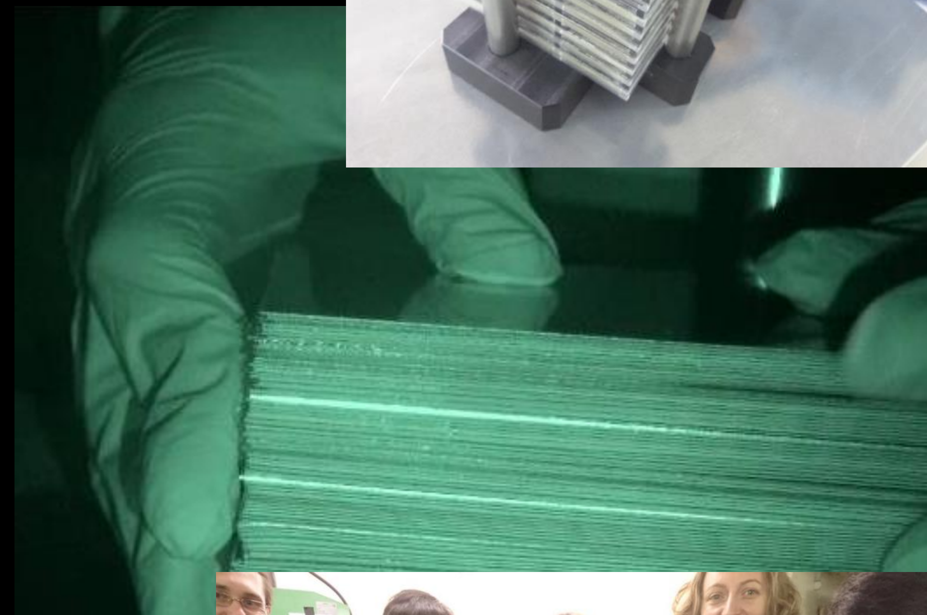
Run	Beam time	Emulsion surface	Goal
2016 test beam		(10 modules) (nonuniform exp.)	Test of the setup Proof of principle
2017 test beam		(~2 modules)	Improvement of exposure scheme
2018 pilot run	1 week	48 m^2 (30 modules)	Test of large data taking and analysis BG estimation with data Physics results (~80 $D_s \to \tau$ detected)
2021- physics run	2 weeks in 2021 + 2 weeks in 2022 (another option: 3.5 weeks in 2021)	545 m^2 (338 modules)	Physics results (~1000 $D_s \to \tau$ detected)

- Preparation for the 2018 pilot run in progress
  - Funding OK
  - Emulsion gel ordered
  - Film production in Nagoya and Bern scheduled in May – Jul.
  - Ready for the run in Aug. or Sep.

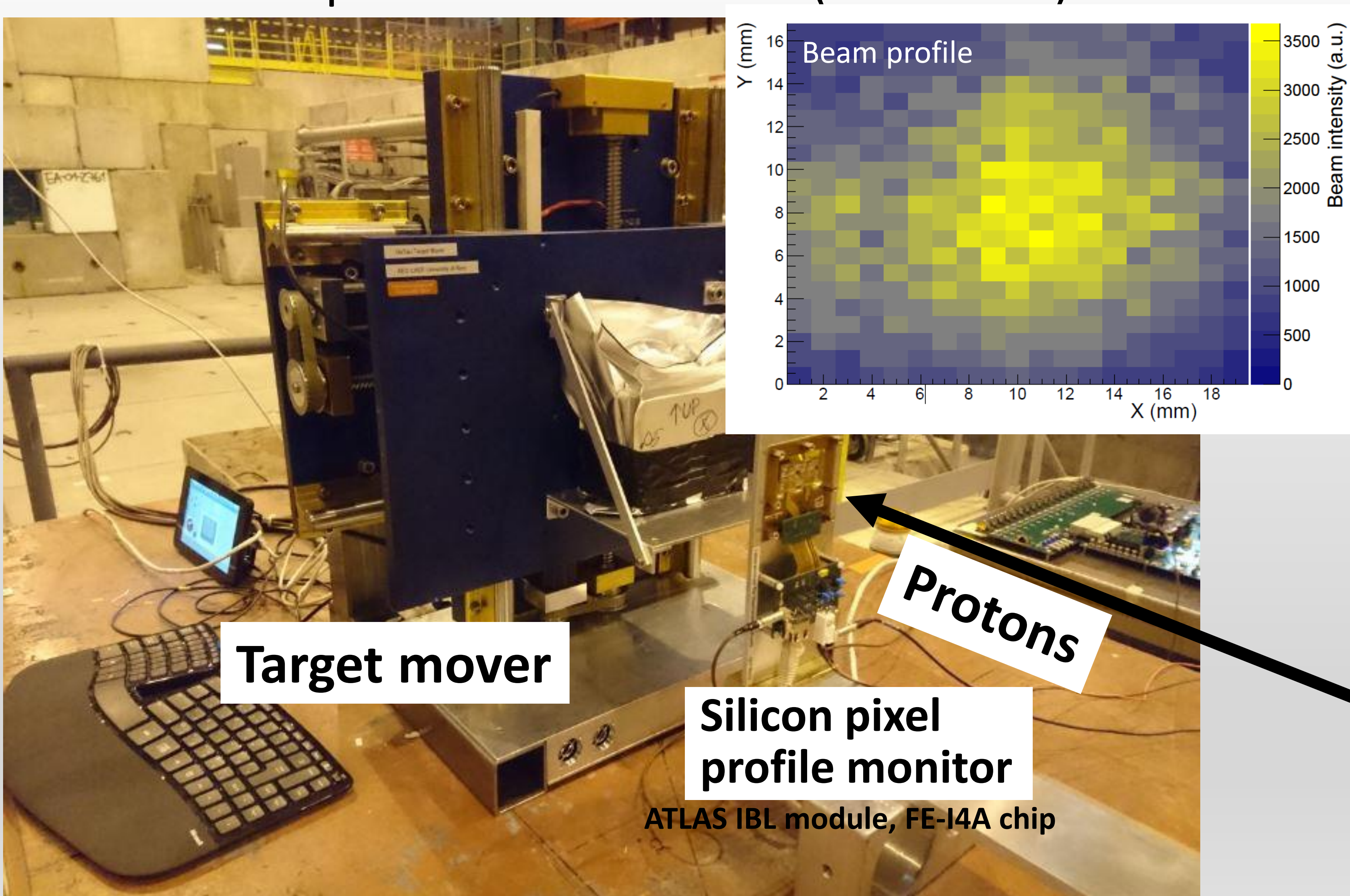
Beam tests in 2016, 2017

- Nov. 2016 H4 beamline
  - Test of the exposure scheme and the setup
  - Proof of principle
- May 2017 H2 beamline
  - Updated exposure sequence (intensity driven synchronization between beam intensity and target mover)
  - Tests to improve angular resolution





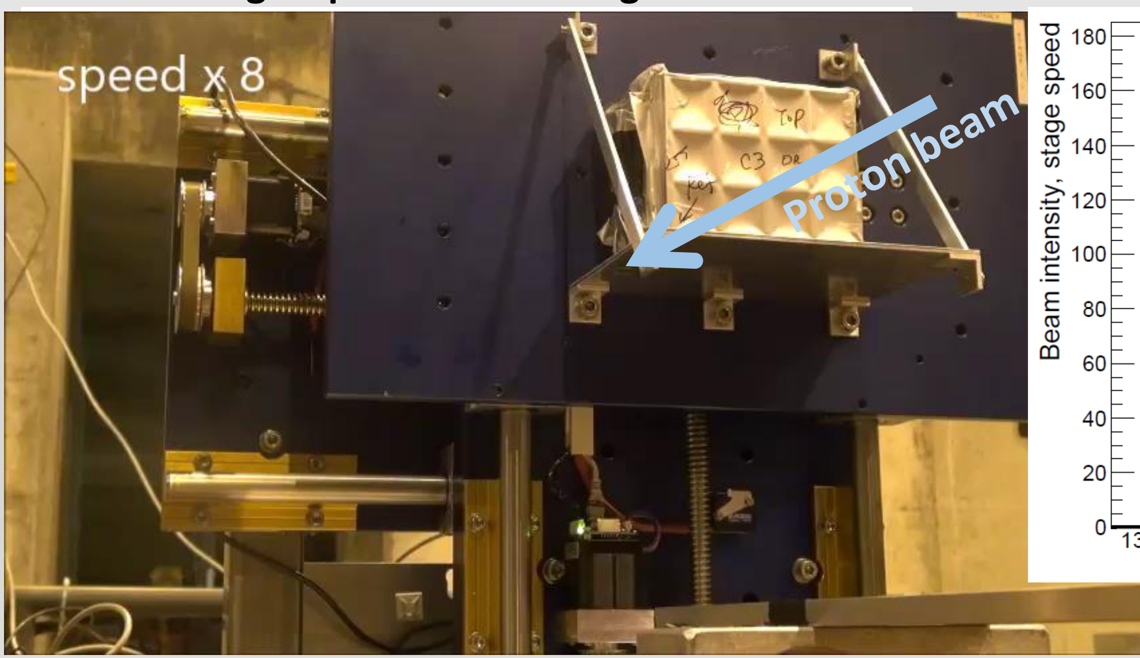
Detector setup at the H4 beamline (beam test)



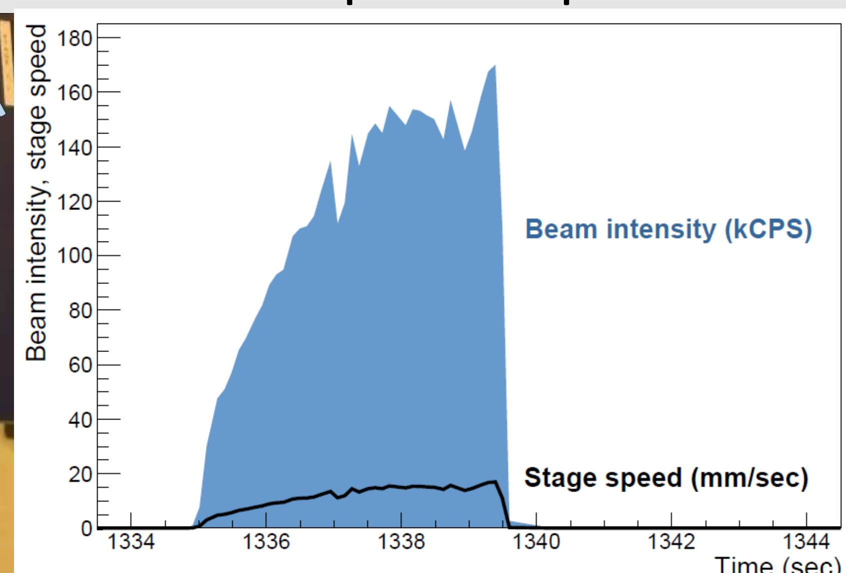
Exposure scheme

- Move detector modules w.r.t. the beam
  - 2016: moved at a constant speed during the spill
  - 2017: intensity driven control by scintillator counter (feedback each 0.2 sec)
- Need ~1 h per module
  - 4 x 11 spills + 20 min to exchange modules

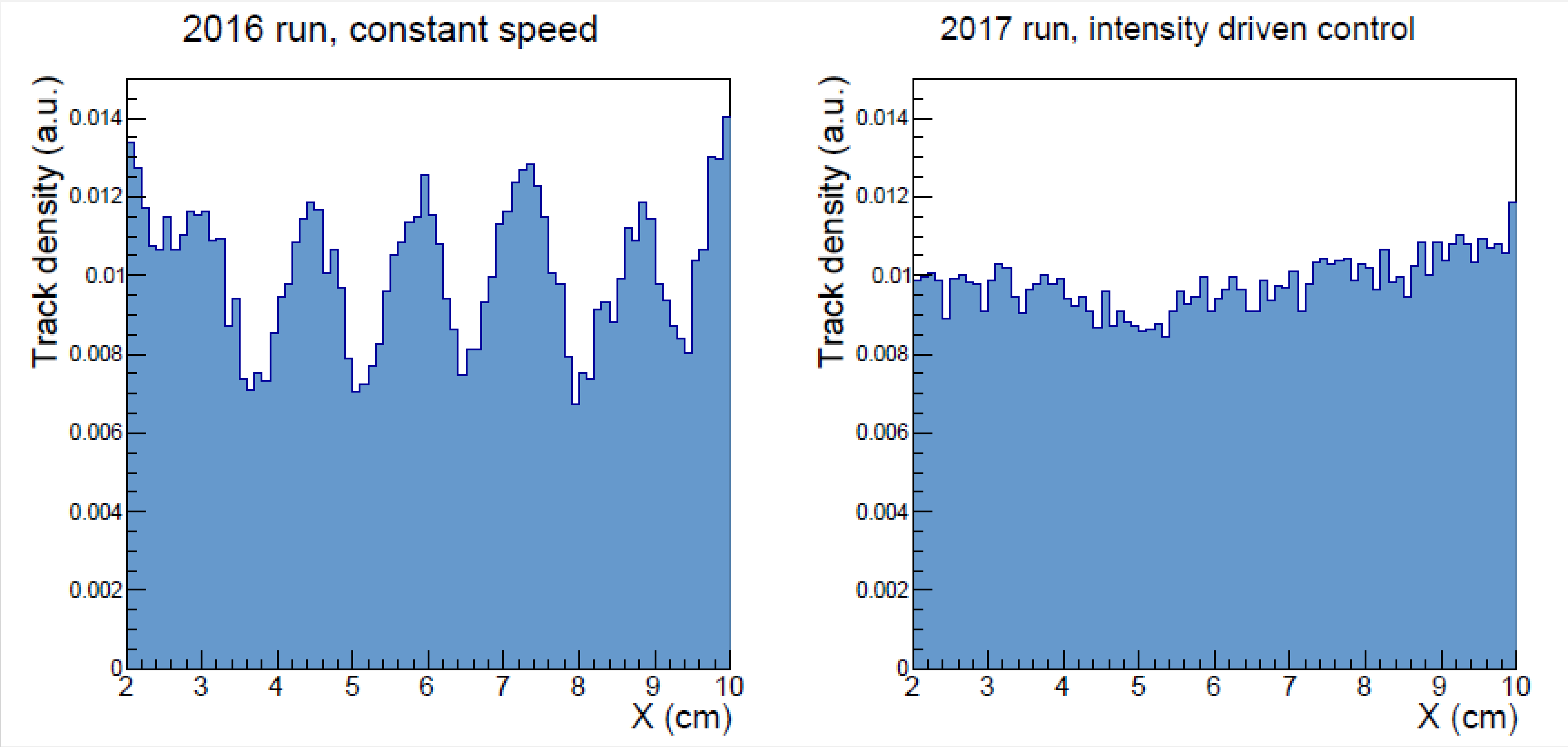
Scanning sequence of the target mover



Time profile in a spill



Position distribution of proton tracks in the detector: comparison between 2016 and 2017

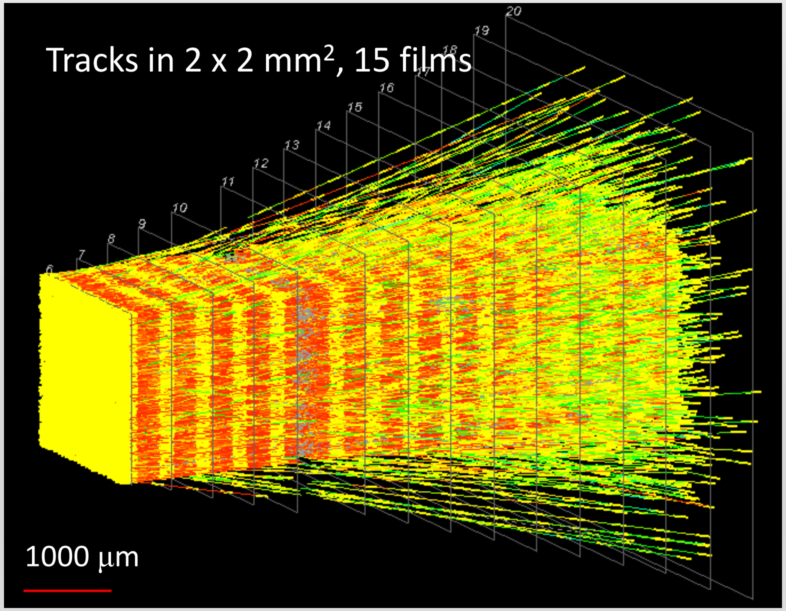


Significant improvement achieved in 2017

Analysis scheme after full area scanning

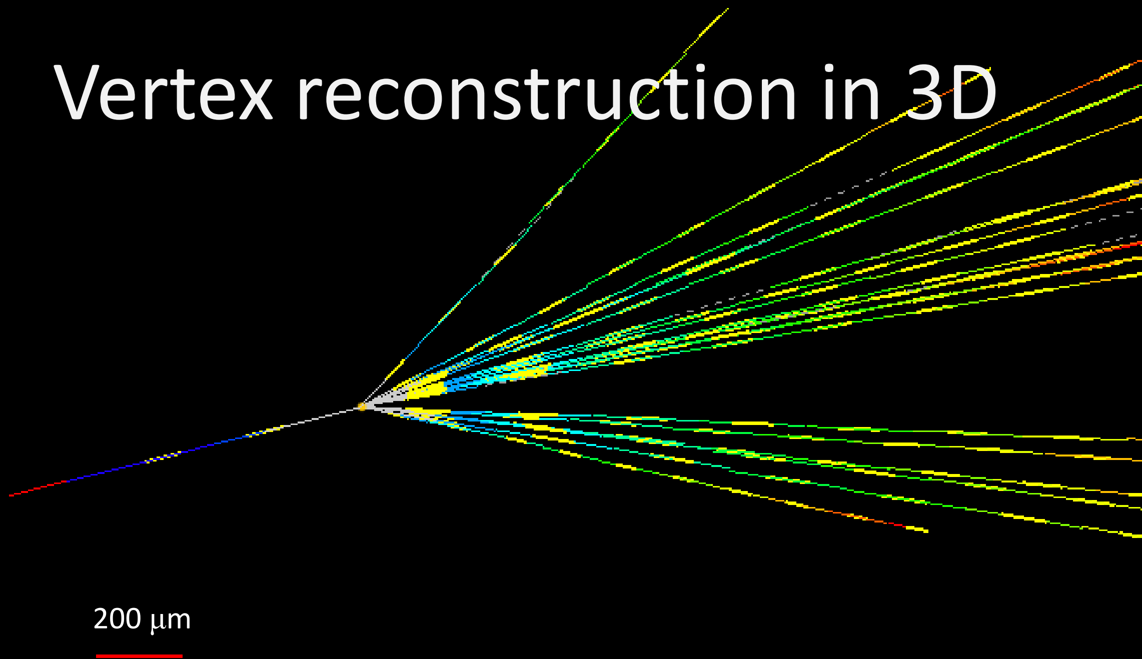
- Conventional tracking (made for OPERA) didn't work in the high track density environment of DsTau
  - OPERA: 100 tracks/cm^2 in wide angular space (θ<500 rad)
  - DsTau: 100,000 tracks/cm^2 in small angular space (θ<10 mrad)

- **New tracking algorithm has been developed and tested**



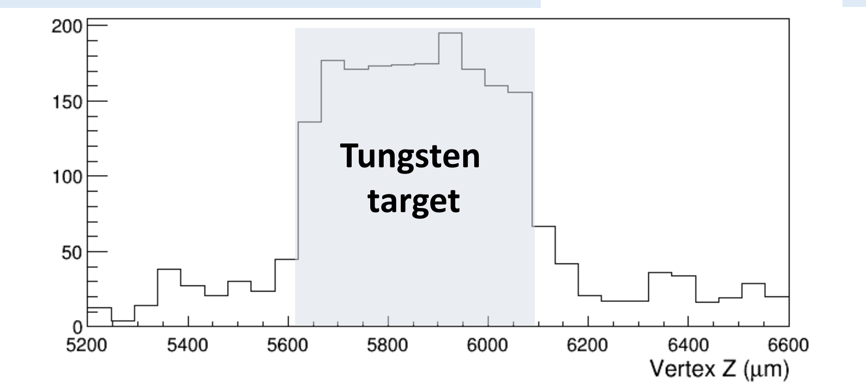
Data from the beam tests (with new track reconstruction)

Vertex reconstruction in 3D



Measured proton beam density in the analyzed region: 4.36×10^5 beam tracks/3.61 cm^2

Z distribution of observed vertices



Interactions in a tungsten plate

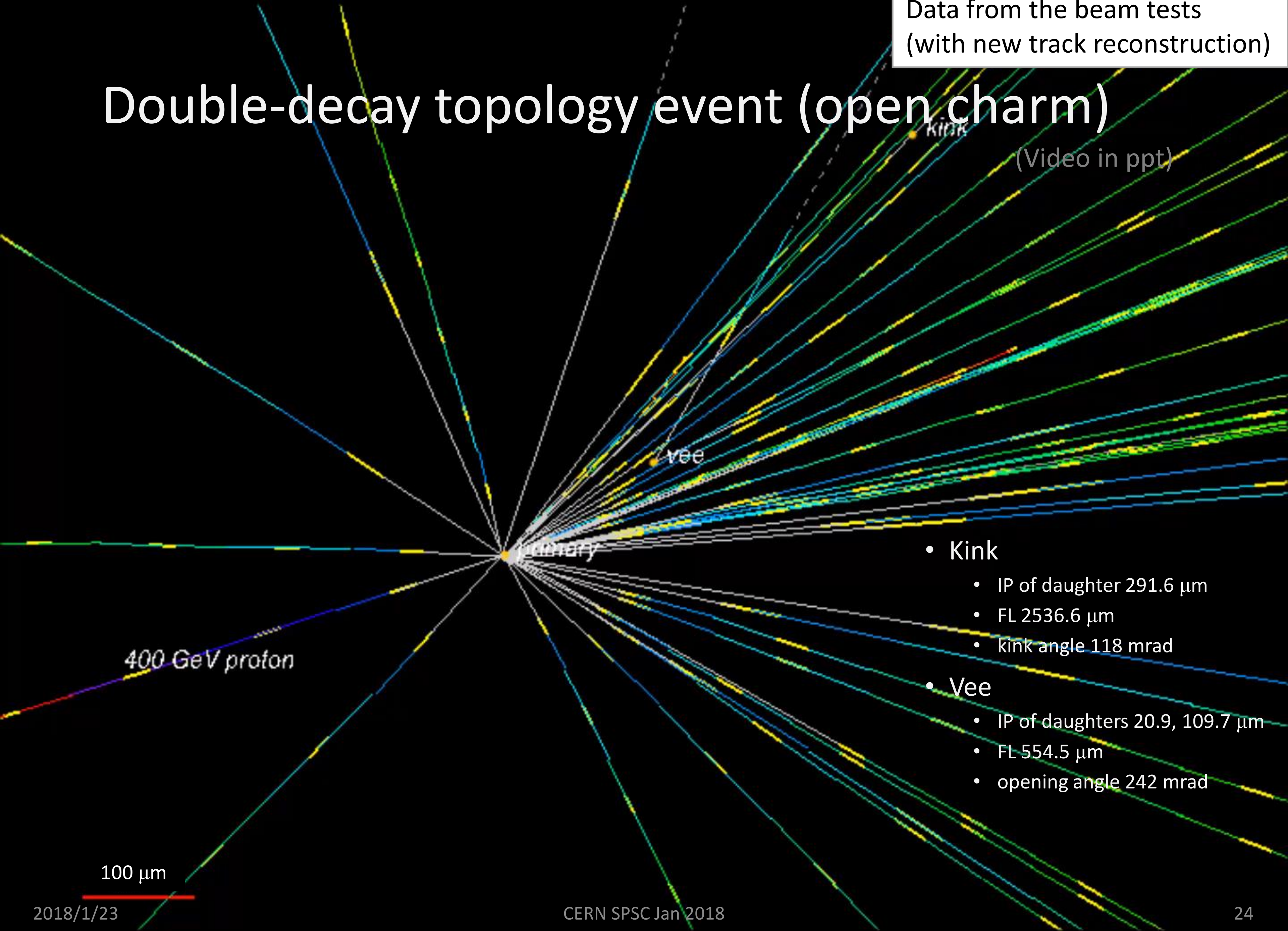
	N vertices
Expected	1860
Observed	With parent 1832
	Without parent 130

- Consistent with the expectation
- Uncertainty due to reconstruction will be reduced by further study

Double-decay topology event (open charm)

Data from the beam tests
(with new track reconstruction)

(Video in ppt)



- 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

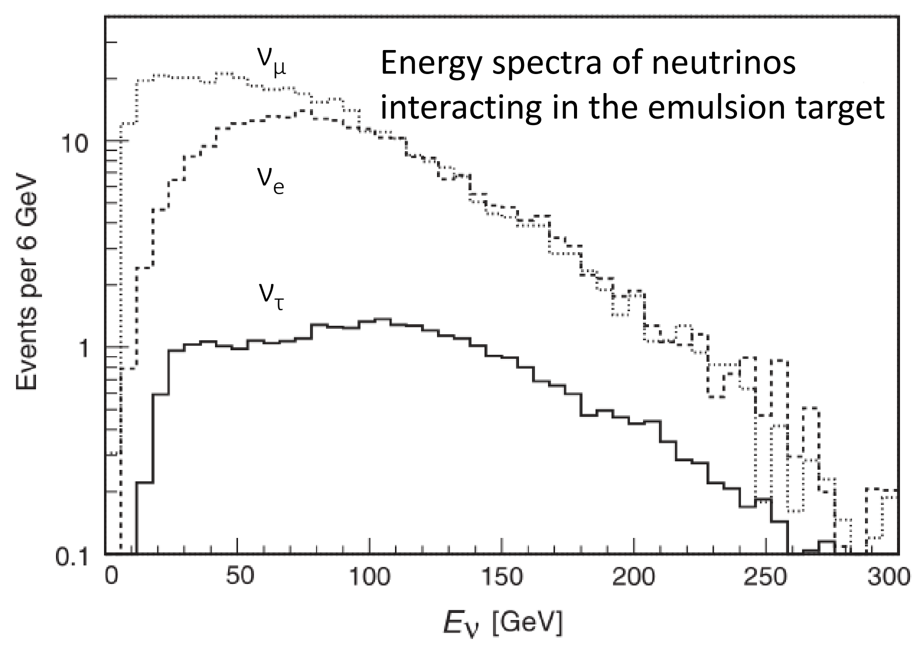
Summary and prospect

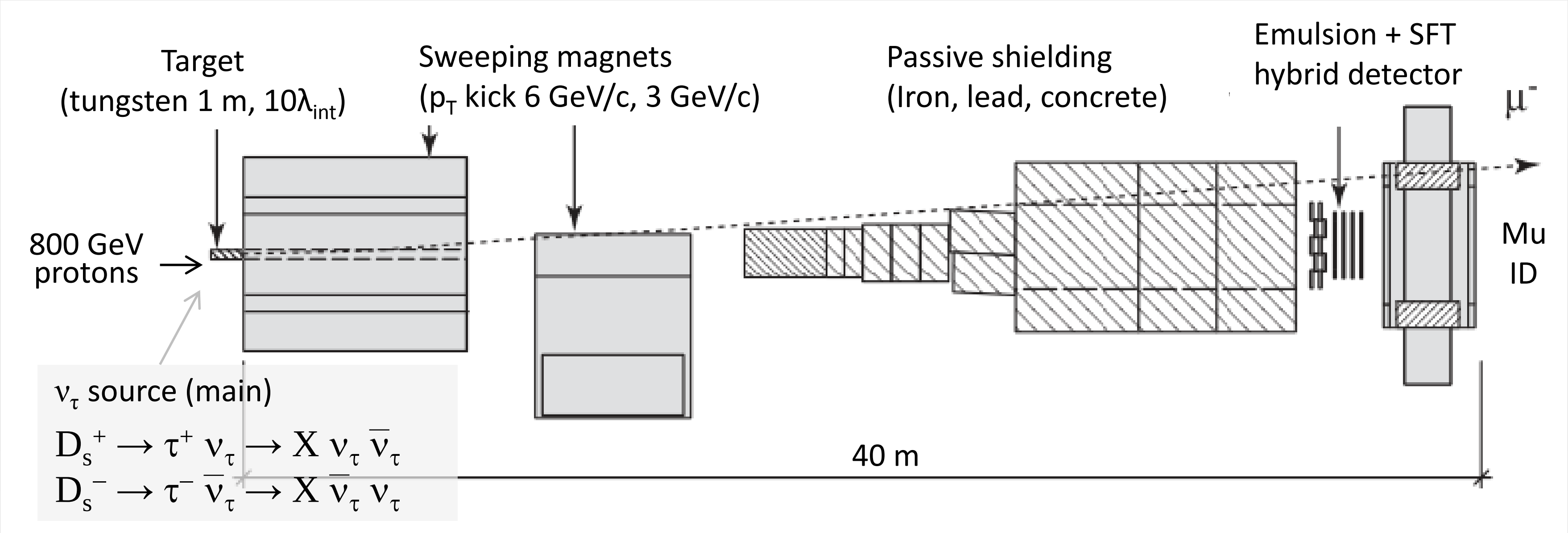
- Motivation to precise measurement of ν_τ CC cross section
  - Search for new physics effect in ν_τ – nucleus interaction
  - Important for future neutrino experiments and astrophysical ν_τ observations
- The DsTau project to measure ν_τ production (D_s differential production cross section), reduce systematic uncertainty in the cross section measurement to 10%
  - Re-evaluation of the DONUT result
  - Important input for future ν_τ experiment: ν_τ program in SHiP
- Aims to detect 1,000 $D_s \rightarrow \tau$ decays in 2.3×10^8 proton interactions
  - Emulsion detectors with nano-precision readout
  - By-products in charm physics (~10^5 charm production)
- Test experiments conducted in 2016-2017
- Pilot run in 2018 and physics run from 2021

Backup

The DONuT experiment (Fermilab E872)

- First direct observation of ν_τ interactions
- 9 ν_τ CC events observed with an estimated background of 1.5 events





ν_τ source (main)

$$D_s^+ \to \tau^+ \nu_\tau \to X\, \nu_\tau\, \bar{\nu}_\tau$$
$$D_s^- \to \tau^- \bar{\nu}_\tau \to X\, \bar{\nu}_\tau\, \nu_\tau$$

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		

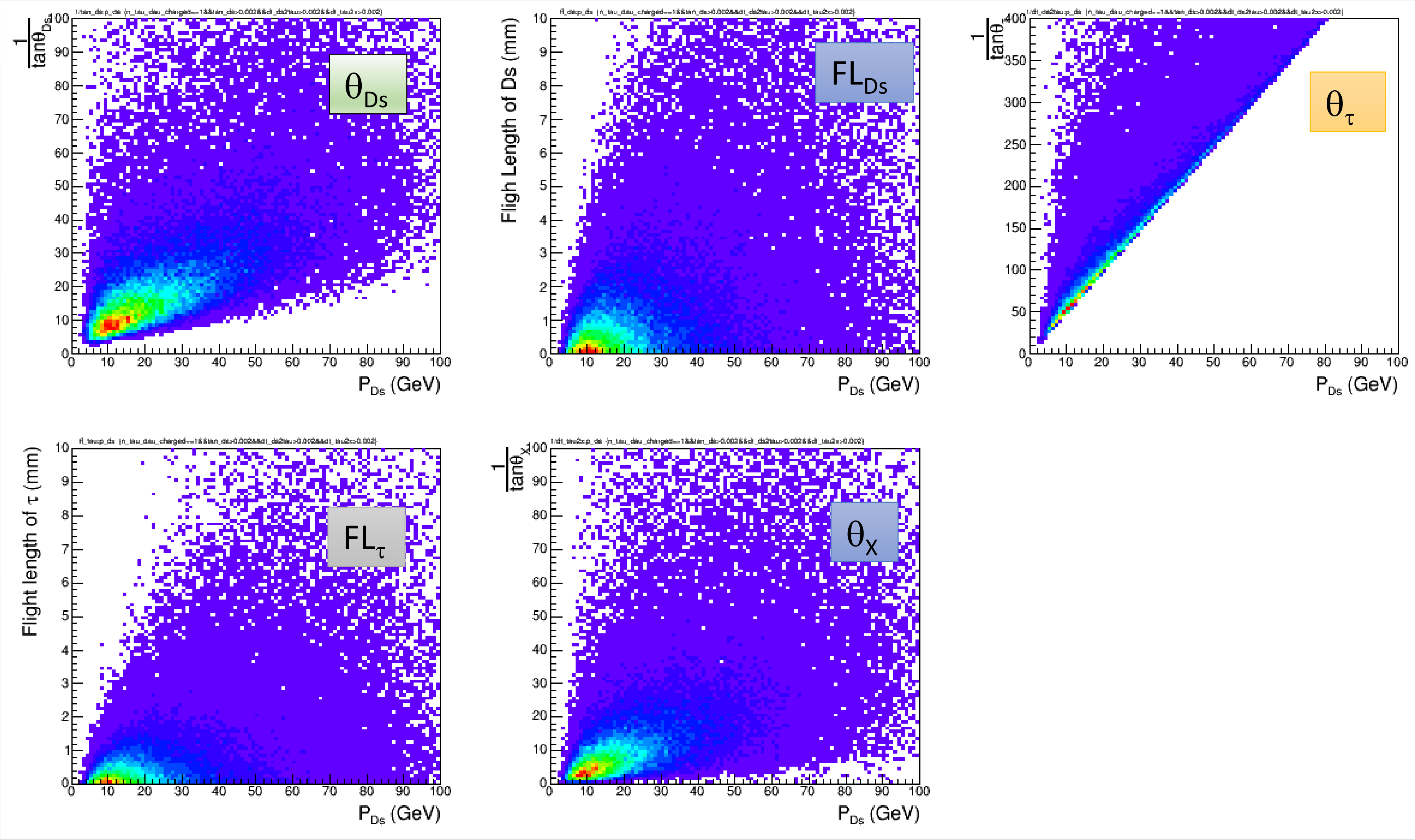
(Results from LHCb at $\sqrt{s}$ = 7, 8 or 13 TeV are not included since the energies differ too much)

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

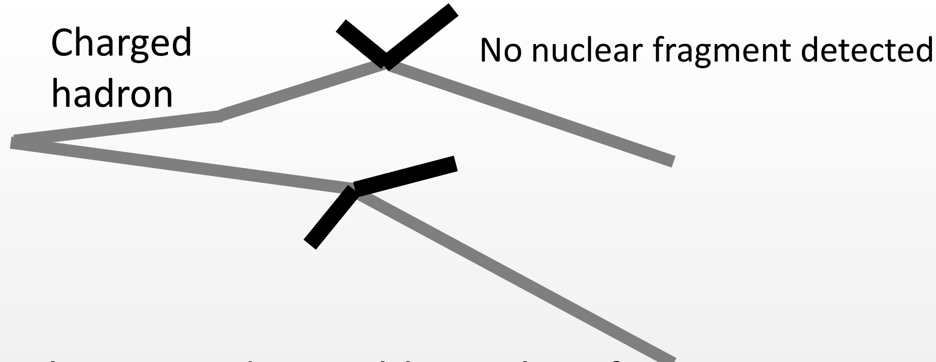
	DsTau	SHiP charm (SPSC-EOI-017)
structure	**Thin target** + decay volume	**ECC** with sliced replica target + magnet + muID
Target	Tungsten / Molybdenum	TZM
Emulsion film area	593 m^2	20 m^2 – 60 m^2
# of modules (runs)	368	40 – 120
pot	4.6×10^9	2×10^7
# of interactions	2.3×10^8	? $O(10^7)$
Charm pair produced	several x 10^5	10^4
Charm pair detection eff	36%	12%
Charm pair detected	a few 10^5	10^3
Ds produced	10^5	10^3
Ds detected (not Ds->tau, no separation from D)	4×10^4	? 100 (20% of D^0)
Ds→ tau → X	10^3	no sensitivity
DAQ	100 kHz (not limited by electric detectors, but stage movement)	<10 kHz (limited by DAQ design)

Topological variables: correlation with p_{Ds}

Sample: 1-prong decay



Background to $D_s \rightarrow \tau$



Main background: hadronic interactions without any detectable nuclear fragments

- Current estimation of hadronic background

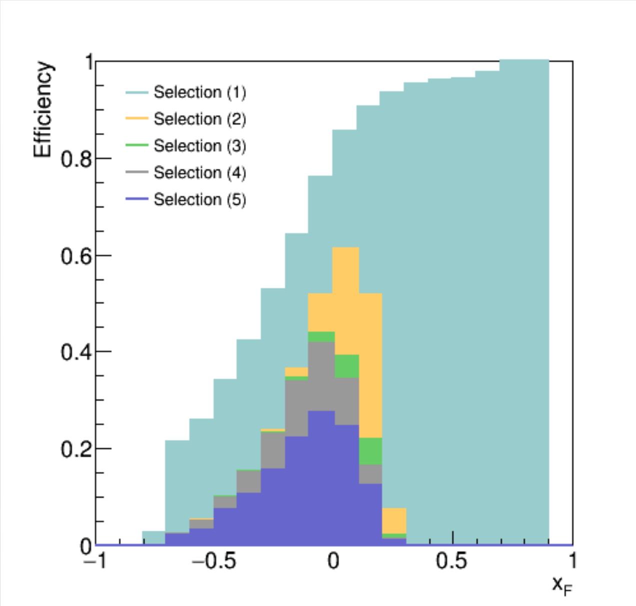
  Using the mean free path for interactions without any detectable nuclear fragments
  11 m for a 5-GeV π beam

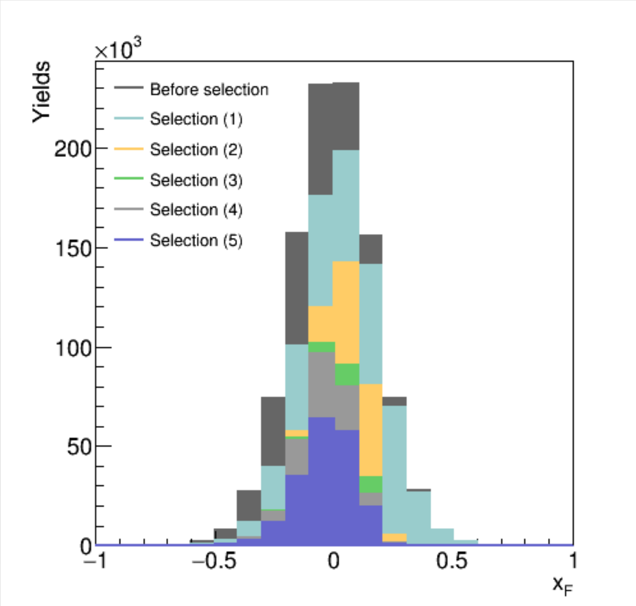
  - A double kink with FL < 5 mm is $(4.5\text{x}10^{-4})^2$ per particle.
  - **BG rate: $9\text{x}10^{-9}$ per proton int.**
  - (Signal rate: D_s production rate $4\text{x}10^{-4}$ x $Br(D_s \rightarrow \tau)$ 5.55% x efficiency 20% = $4\text{x}10^{-6}$ per proton int.)

- **Study with FLUKA** in progress
- **Validation from real data** planned with the 2018 data

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

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





Indication of possible non-universality in leptonic decays of B mesons

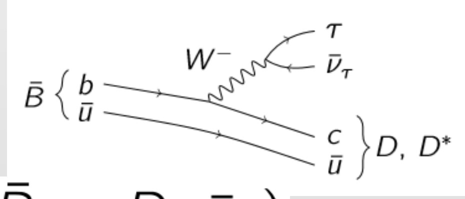
- W decays (LEP combination)

$$\mathcal{B}(W \to \mu\nu_\mu)/\mathcal{B}(W \to e\nu_e) = 0.994 \pm 0.020$$

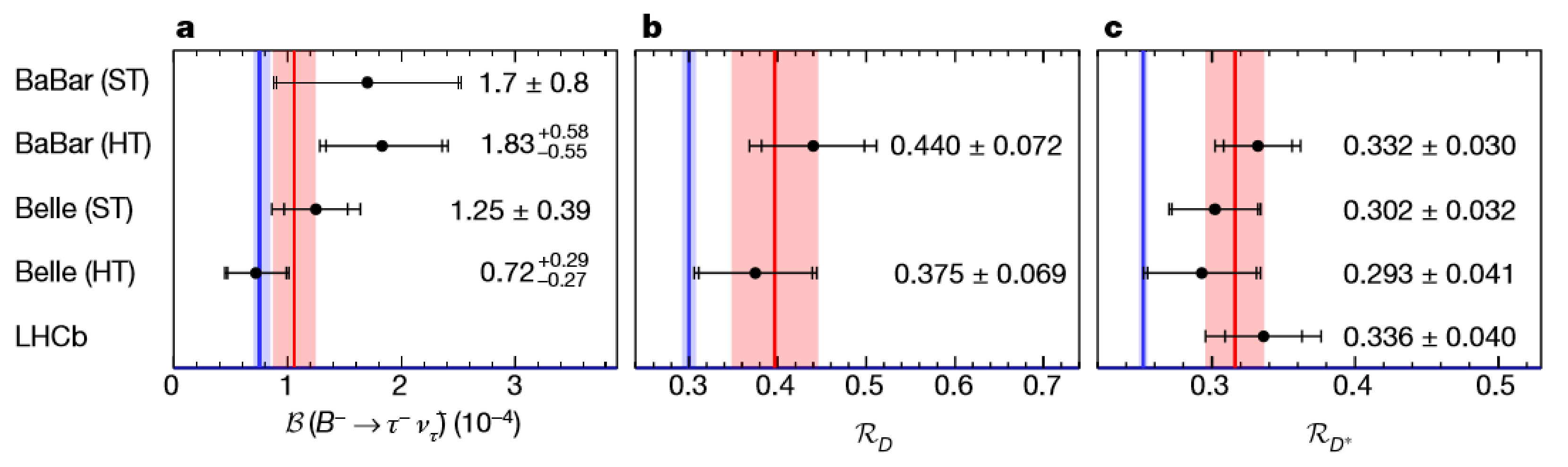
$$\frac{\mathcal{B}(W \to \tau\nu_\tau)}{\frac{1}{2}\left(\mathcal{B}(W \to e\nu_e) + \mathcal{B}(W \to \mu\nu_\mu)\right)} = 1.077 \pm 0.026$$

- B-meson decays

Review, doi:10.1038/nature22346



$$\mathcal{B}(B \to \tau\bar{\nu}_\tau) \qquad R_D = \mathcal{B}(\bar{B} \to D\tau\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D\mu\bar{\nu}_\mu)$$



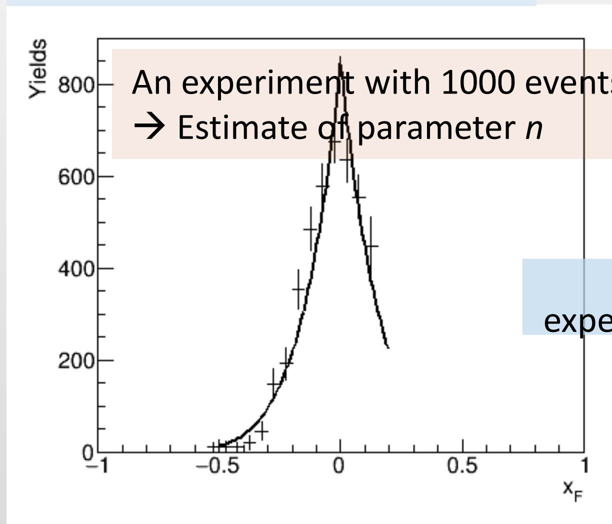
Estimation of parameter *n* for DONUT re-evaluation

Ds differential cross section

Parametrization used in DONUT

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

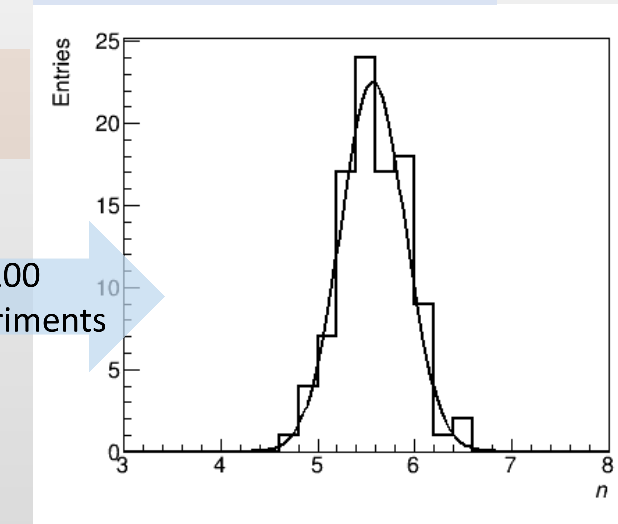
Reconstructed x_F
(corrected by the efficiency)



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 xF distribution to be applied (method will be investigated)