Study of tau-neutrino production at the CERN SPS

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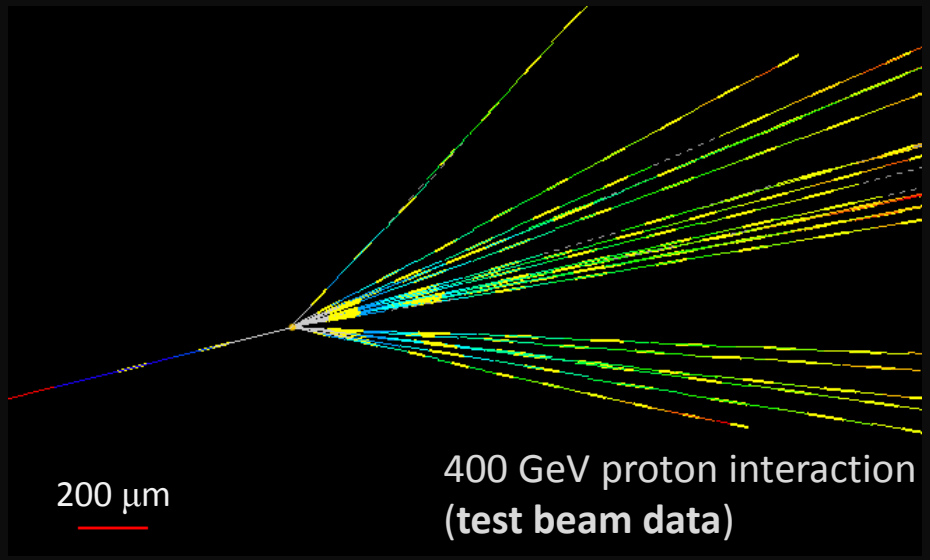
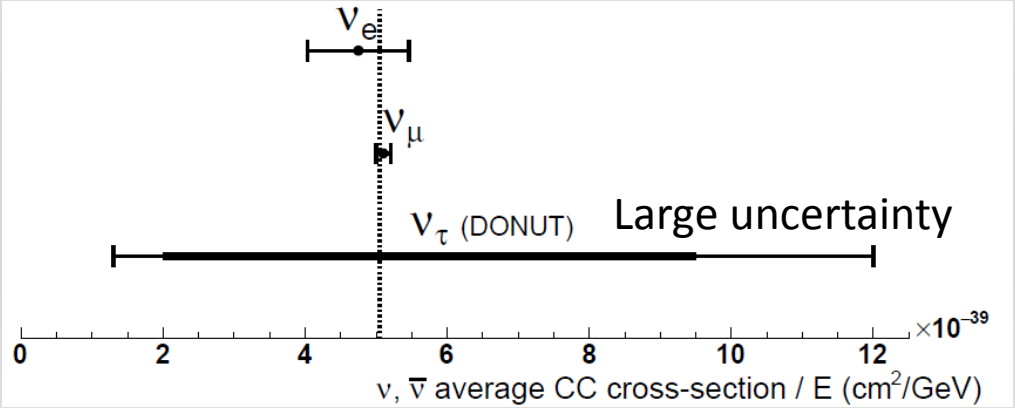
for the DsTau collaboration



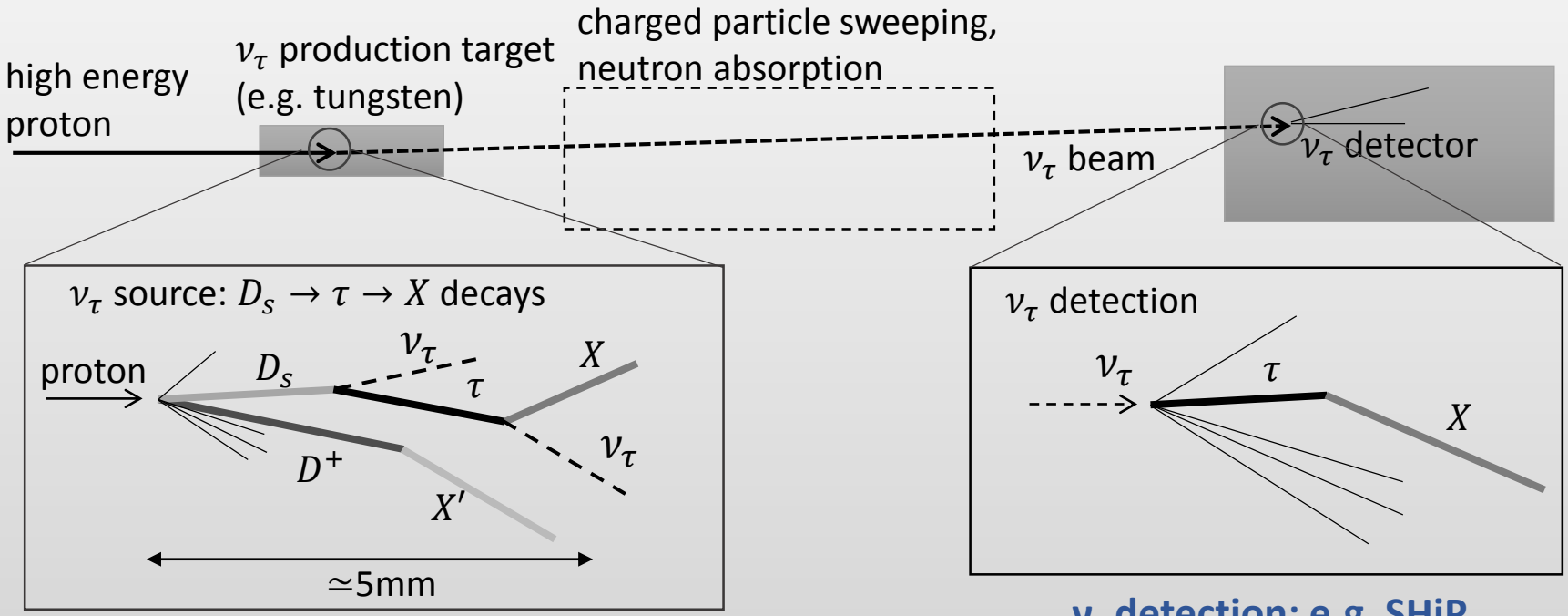
Physics motivations

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

- Precise measurement of ν_τ CC cross section:
  - Search for new physics effect in ν_τ – nucleon CC interactions
    - Test of lepton non-universality
  - Important input for future neutrino experiments (Hyper-K, DUNE) and astrophysical ν_τ observations (IceCube)



Concept of ν_τ cross section measurement



ν_τ production study: DsTau

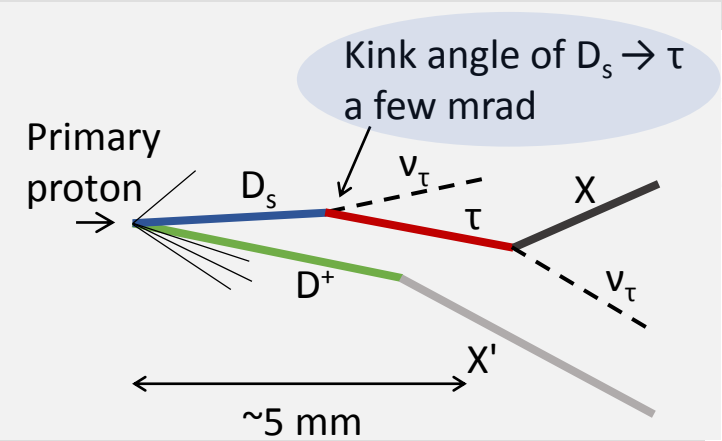
- No experimental data on the Ds differential cross section
- Large systematic uncertainty (~50%) in the ν_τ flux prediction

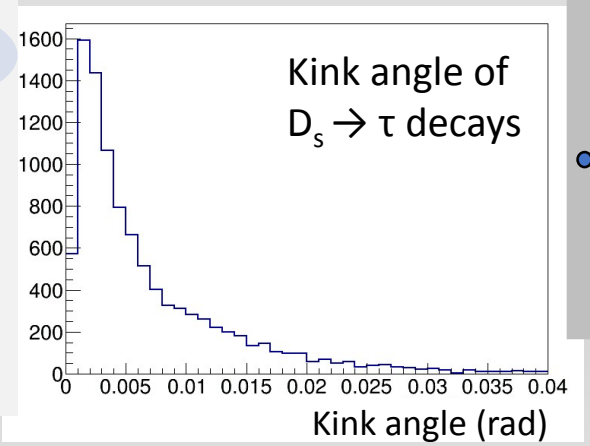
ν_τ detection: e.g. SHiP

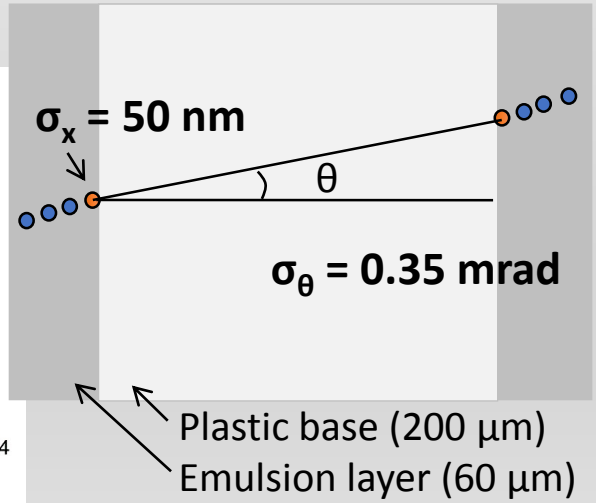
- Statistical uncertainty 33% in DONUT
- Will be reduced to the 2% level in future experiments

The DsTau project at the CERN SPS (SPSC-P-354)

- **Goals**
  - Measurement of ν_τ production
    - Measurement of Ds differential production cross section
  - Reduction of 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**
  - Detection of double-kink + another decay topology within a few mm



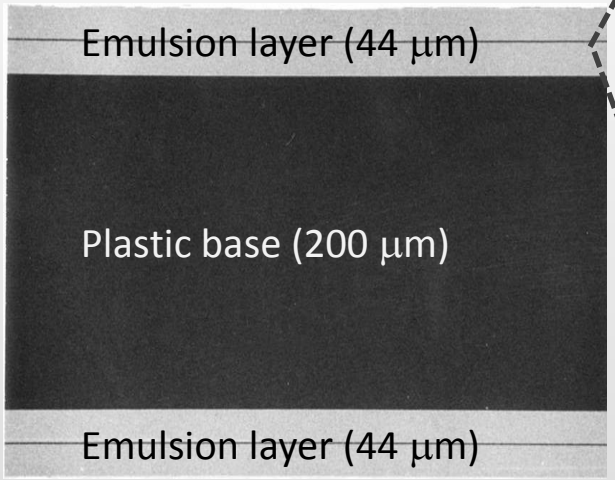




Emulsion detectors:
3D tracking device with 50 nm precision

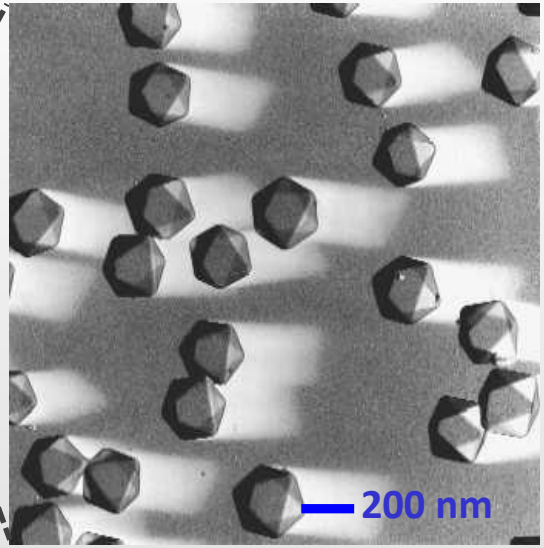
Emulsion film

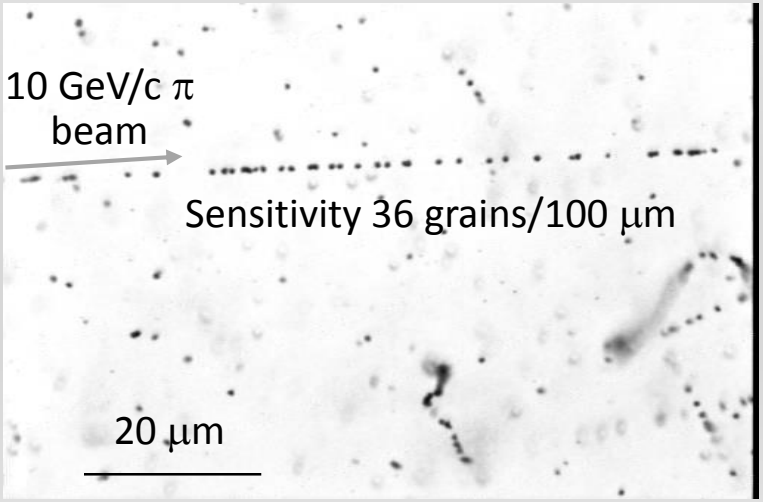
Cross-sectional view

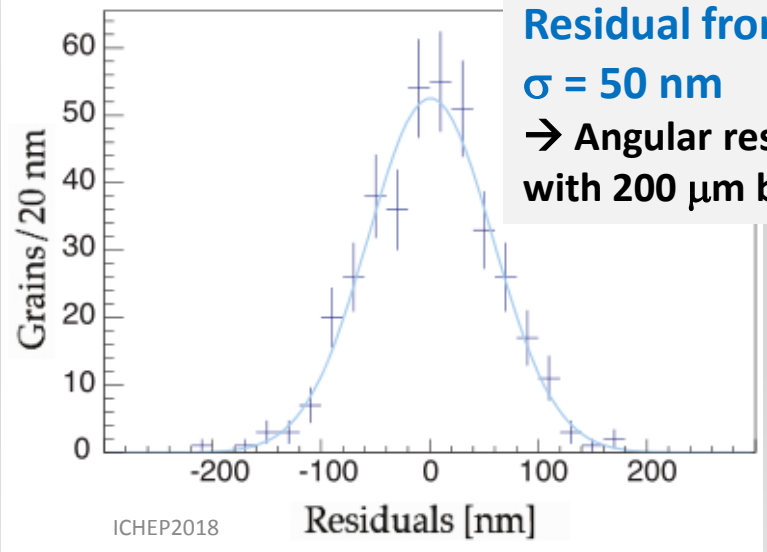


AgBr crystal

10^{14} crystals in a film





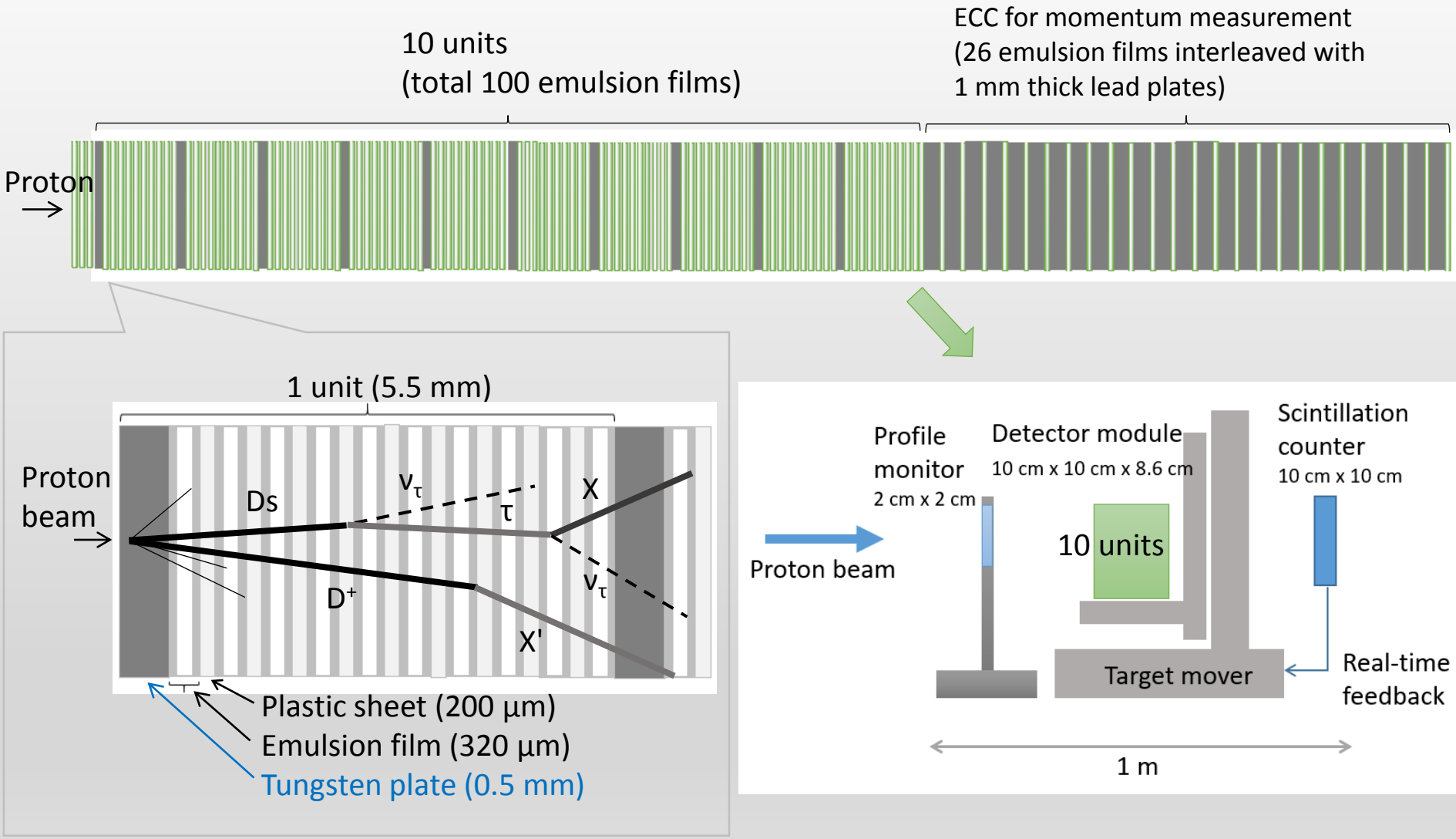


Residual from fitted track

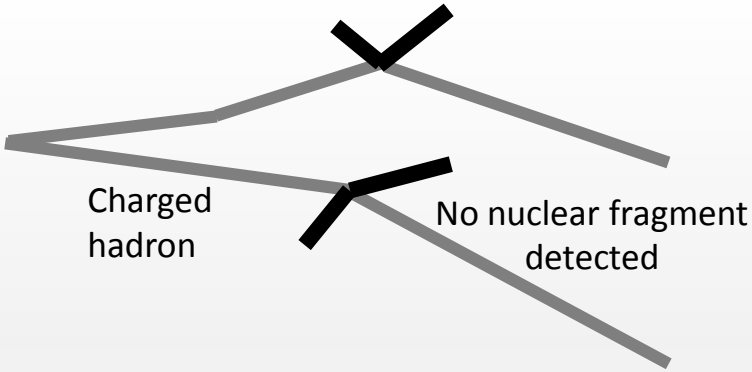
σ = 50 nm

→ Angular resolution 0.35 mrad with 200 μm base

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



Signal and background rates



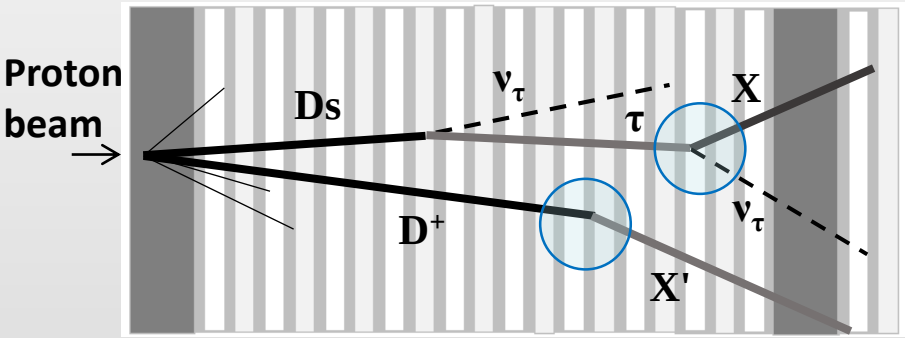
- **Signal**: Ds → τ → X events (double-kink + another decay topology within a few mm)
- Signal rate: 2.2×10^{-5} /proton int. x eff. 20%
- To detect 1000 Ds → τ → X events, 2.3×10^{8} proton interactions (4.6×10^{9} pot) are needed

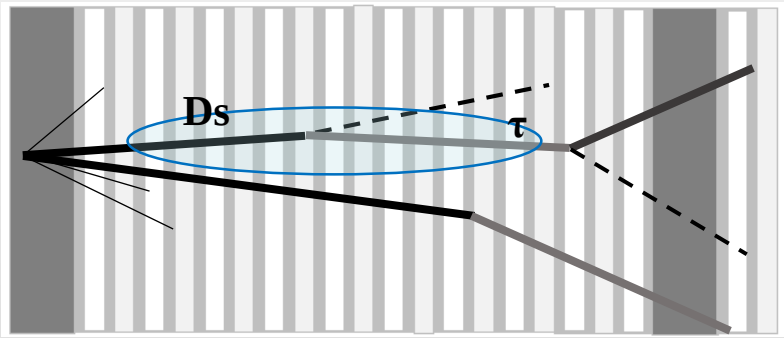
- **Main background**: hadronic interactions without any detectable nuclear fragments
  - Test beam data with a 5-GeV π beam
    - A kink with FL <5 mm: 4.5×10^{-4} /particle
  - Study with FLUKA is in progress
    - A kink with FL <5 mm: 2.4×10^{-4} /particle
- BG rate (double kink + another kink): 1.4×10^{-9} /proton int.
  - Combination with decays is to be studied
- **Validation from real data is planned with the 2018 data**

Analysis scheme for double-kink search

- Full area scanning by the fast scanning system
- Select decays with Δθ > 20 mrad

- Precision measurement to detect Ds -> τ decay (a few mrad)

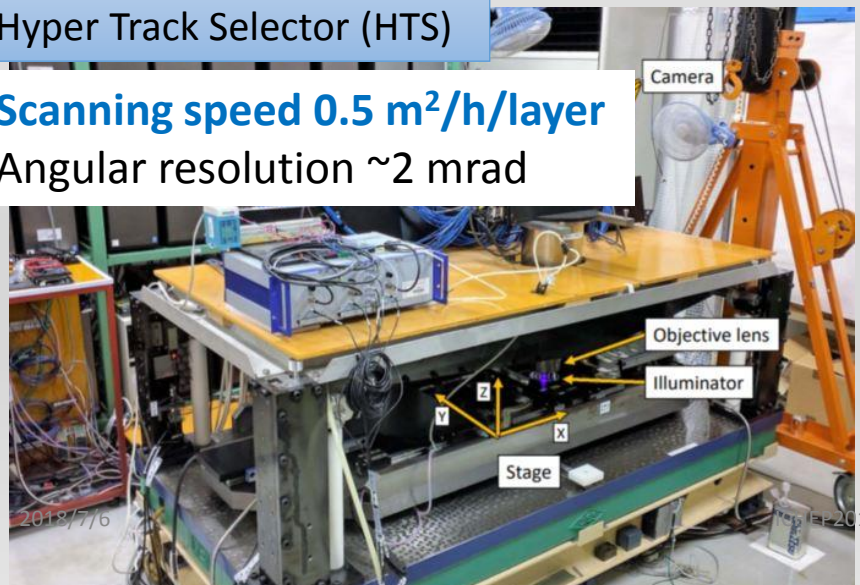




Hyper Track Selector (HTS)

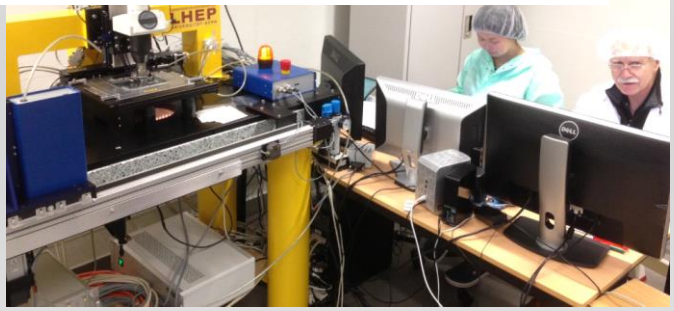
Scanning speed 0.5 m²/h/layer

Angular resolution ~2 mrad



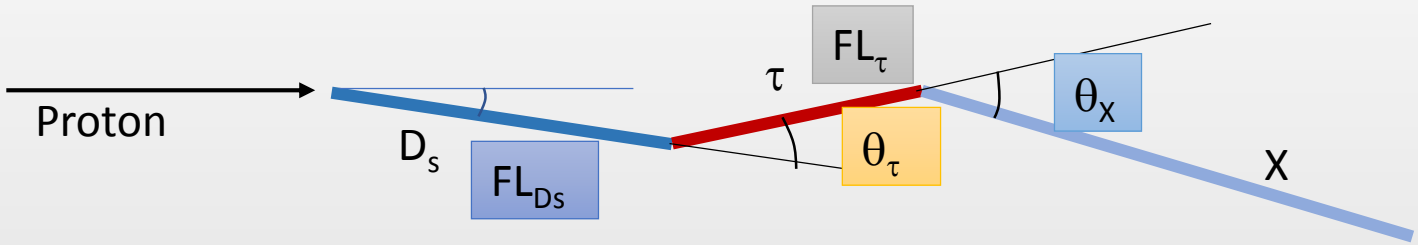
Dedicated high-precision systems

Angular resolution ~0.3 mrad



New method for Ds momentum reconstruction

by Artificial Neural Network using topological variables

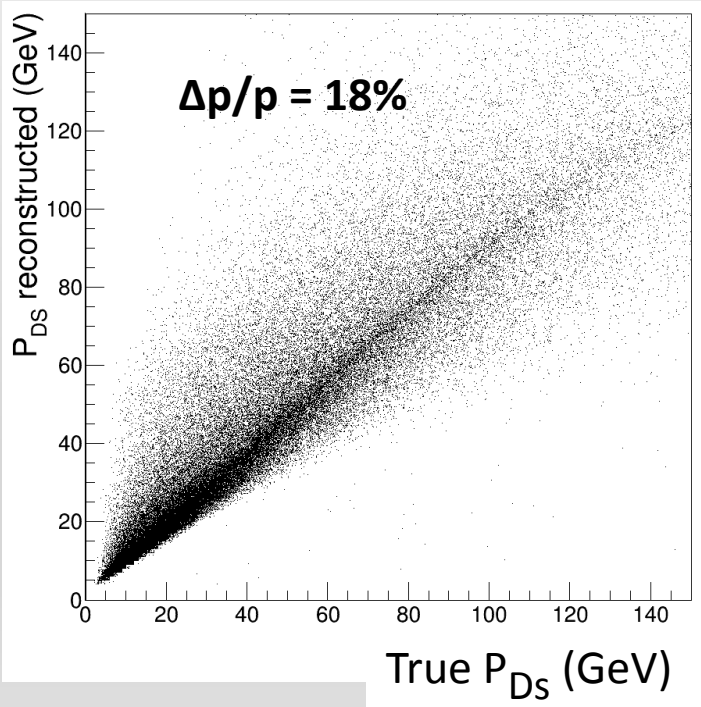


FL: flight length

- Difficult to measure Ds momentum directly due to short lifetime

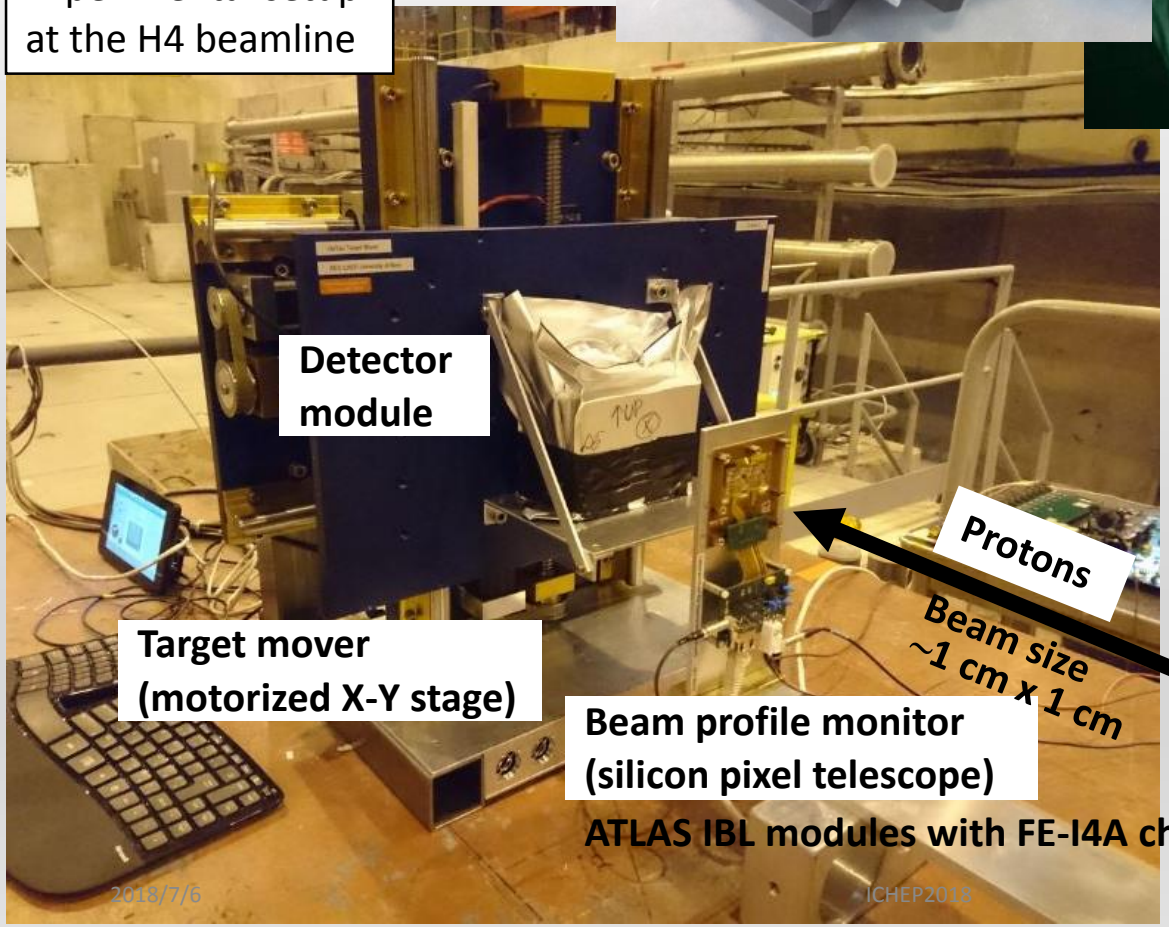
→ Ds momentum reconstruction by topological variables

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



Beam tests

Experimental setup at the H4 beamline

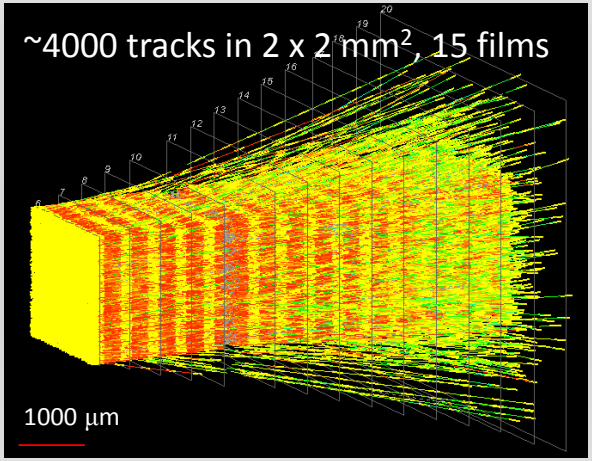


- Nov. 2016 H4 beamline
  - Test of the exposure scheme and the setup
  - Proof of principle
- May 2017 H2 beamline
  - Updated exposure sequence (intensity driven synchronization between beam intensity and target mover)
  - Tests to improve angular resolution

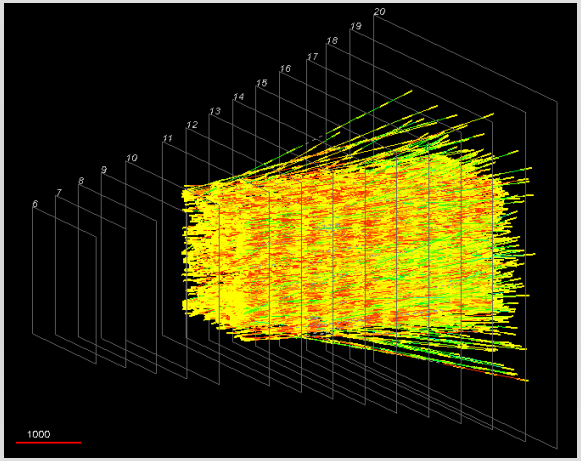
Reconstruction of proton interactions in tungsten

- 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)
  - (~100 PB will be processed in the 2018 pilot run (50 m^2))
- Track density
  - OPERA: 100 tracks/cm2 in wide angular space (θ<500 rad)
  - DsTau: 100,000 tracks/cm2 in small angular space (θ<10 mrad)

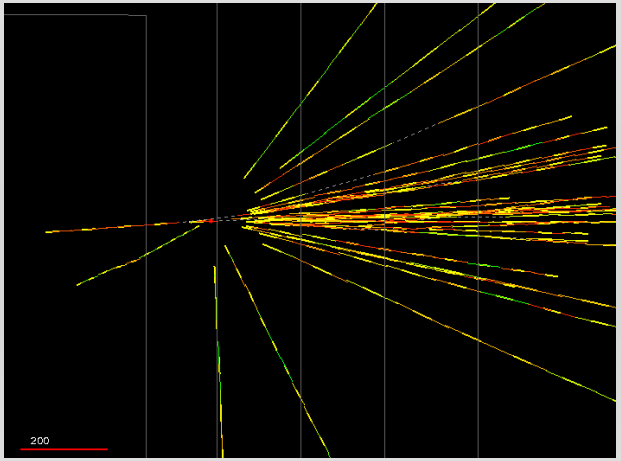
Reconstructed tracks



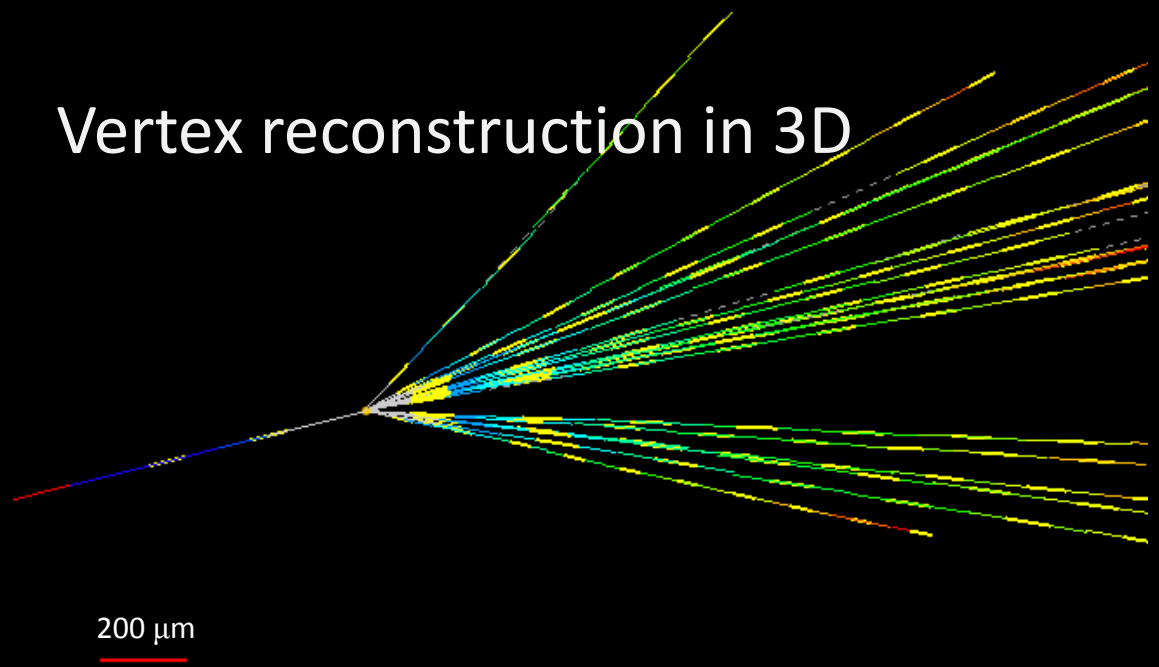
Tracks starting after tungsten



Vertex reconstruction

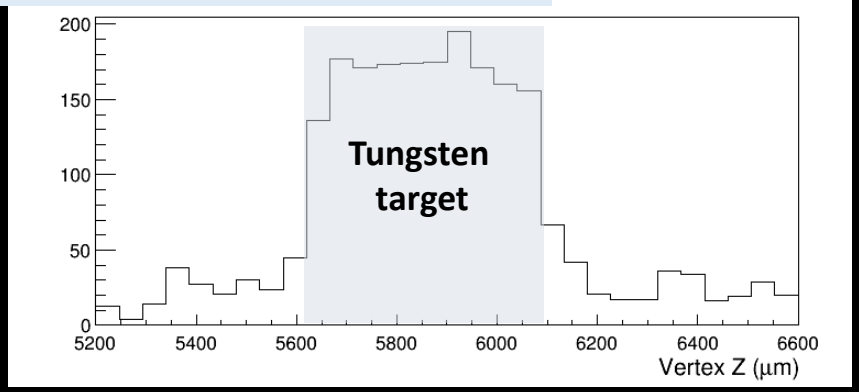


Vertex reconstruction in 3D



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

Z distribution of observed vertices

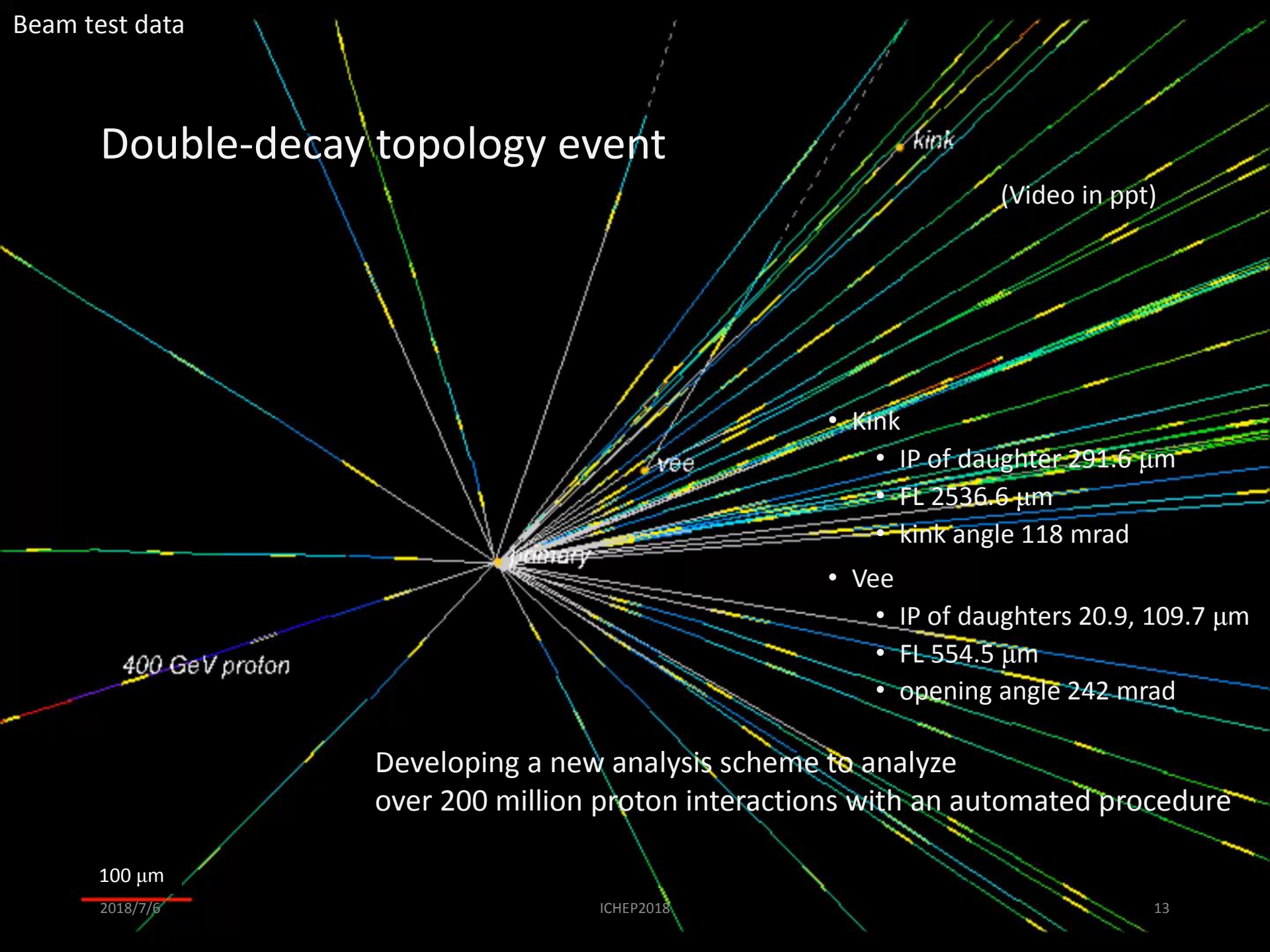


Interactions in a tungsten plate

	N vertices
Expected	1860
Observed	With parent 1832
	Without parent 130

Consistent with the expectation

Double-decay topology event



(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

Developing a new analysis scheme to analyze
over 200 million proton interactions with an automated procedure

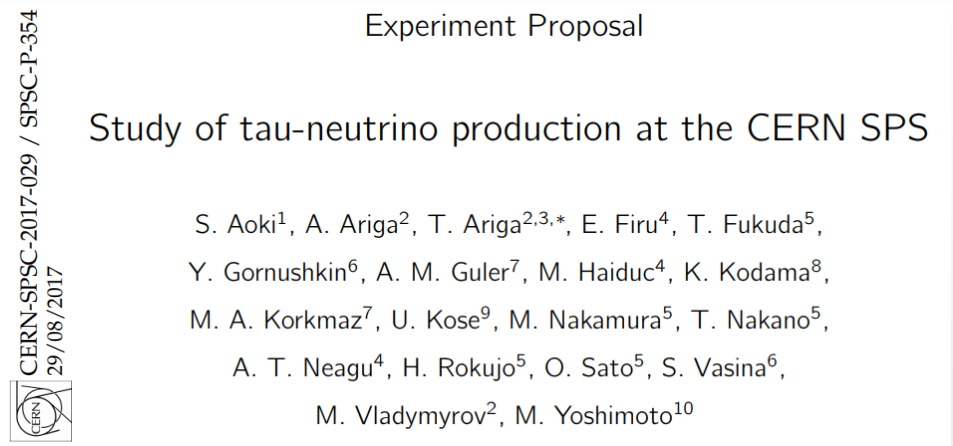
Status of the project

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

- Presentation at the 128th Meeting of the SPSC (open session): https://indico.cern.ch/event/694185/
- Reviewed during the SPSC meeting, Jan. 2018

→ **Positive feedback**

- **"The 2018 run has been approved and the Committee recommends that the beam time requested for 2021 will be granted."**



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]

Collaboration

Japan:
Aichi University of Education
Kobe University
Kyushu University
Nagoya University

Romania:
Institute of Space Science

Russia:
JINR-Joint Institute for Nuclear Research

Switzerland:
University of Bern

Turkey:
METU-Middle East Technical University

The 2018 pilot run

Goal

- Test of large data taking and analysis
- BG estimation with data
- Physics results (~80 Ds → τ detected)

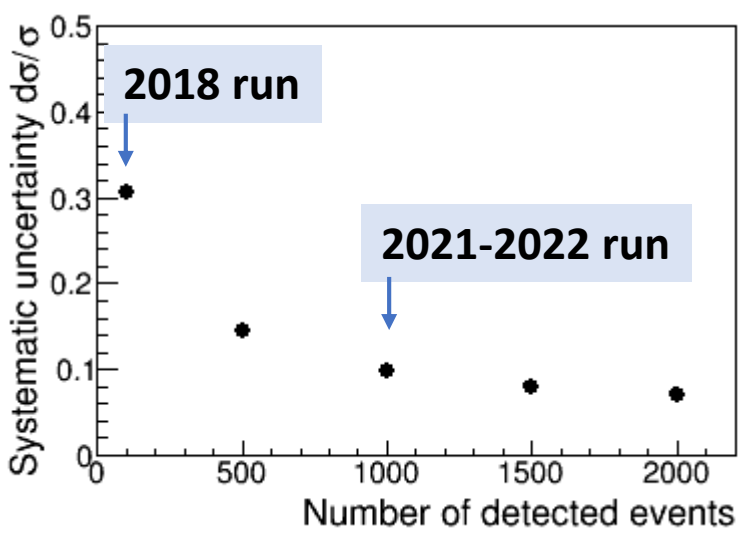
- Film production in progress (June – August 2018)
  - Needed: 48 m^2 (3900 films)
  - Production speed: ~5 m^2/week

~50% of the films already produced!

Emulsion
Base
Emulsion

Expected performance

Run	Beam time	Emulsion surface	Systematic uncertainty for the cross section measurement
2018 pilot run	1 week	48 m^2 (30 modules)	**30% → Re-evaluation of the DONUT result**
2021 physics run	2 weeks	545 m^2 (338 modules)	**10% → Input for future measurement**
2022 physics run	2 weeks		



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	0.05	0.05
Decay branching ratio ($D_s \rightarrow \tau$)	0.23 (0.04 at present)		
Target atomic mass effects	0.14		

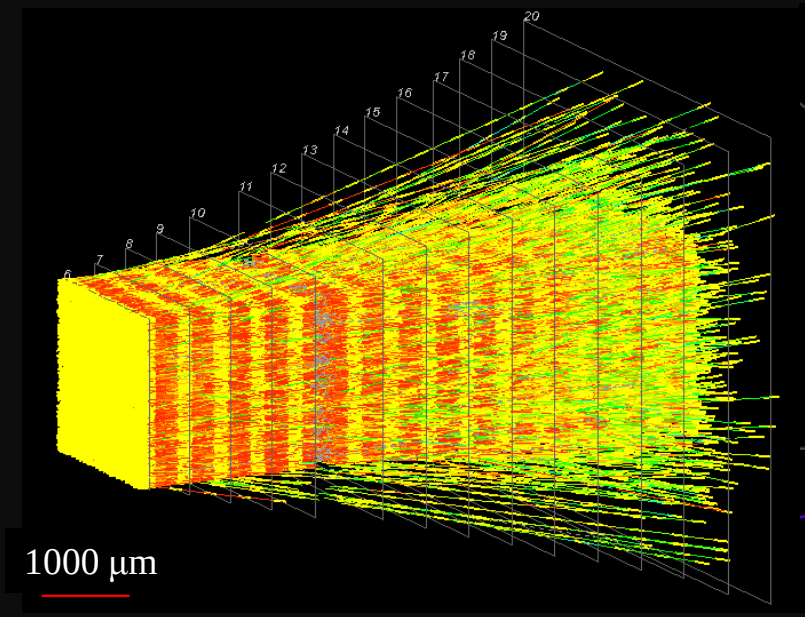
Aiming at ~10% precision to look for new physics effects in ν_τ -nucleon CC interactions

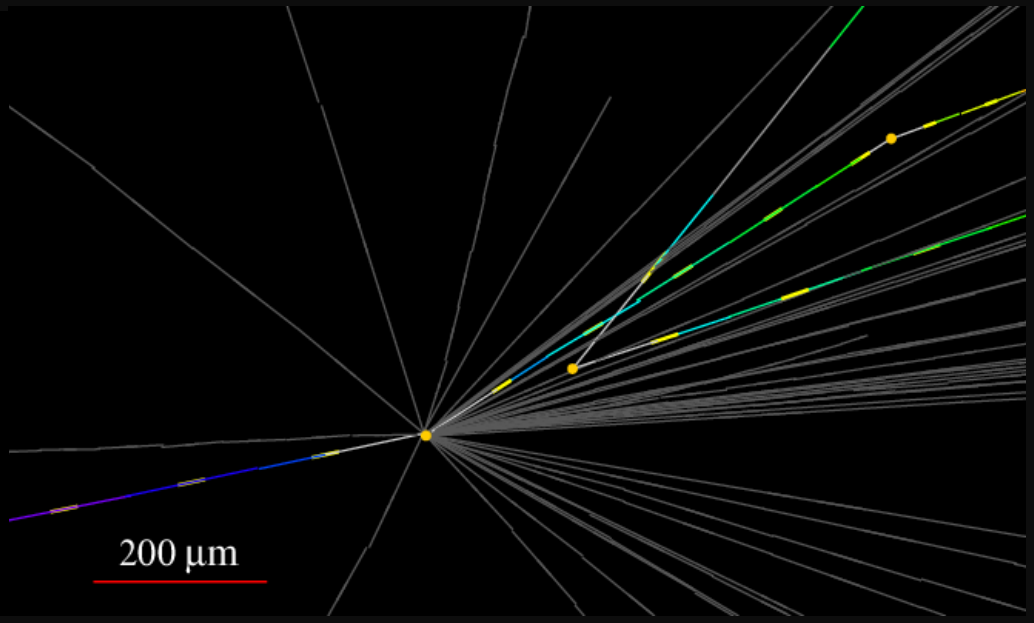
Summary

- A new precise measurement of the ν_τ cross section is important
  - to test new physics effects in ν_τ –nucleon CC interactions
  - for neutrino oscillation experiments and astrophysical ν_τ observations

- The DsTau project has been proposed at the CERN SPS to study ν_τ production (SPSC-P-354)
- This project aims to
  - detect 1000 Ds → τ decays in 2.3×10^8 proton interactions employing emulsion detectors with a spatial resolution of 50 nm
  - reduce the systematic uncertainty in the ν_τ cross section measurement from >50% to 10%
- A pilot run in 2018 has been approved and beam time for a physics run in 2021 recommended by the CERN-SPSC.
- Preparation is in progress for the pilot run in August 2018!

Thank you for your attention

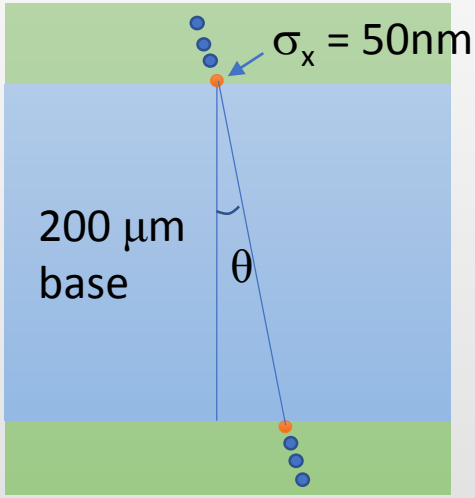


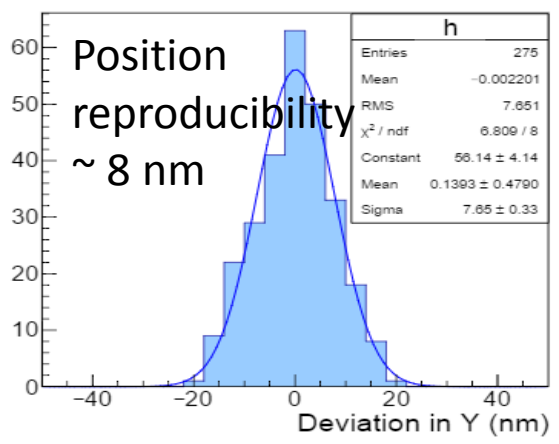


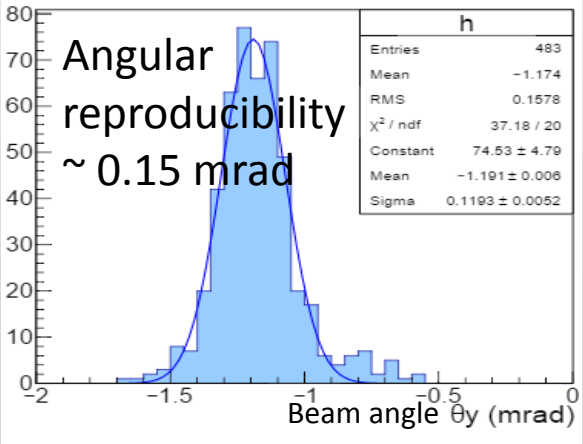
Backup

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

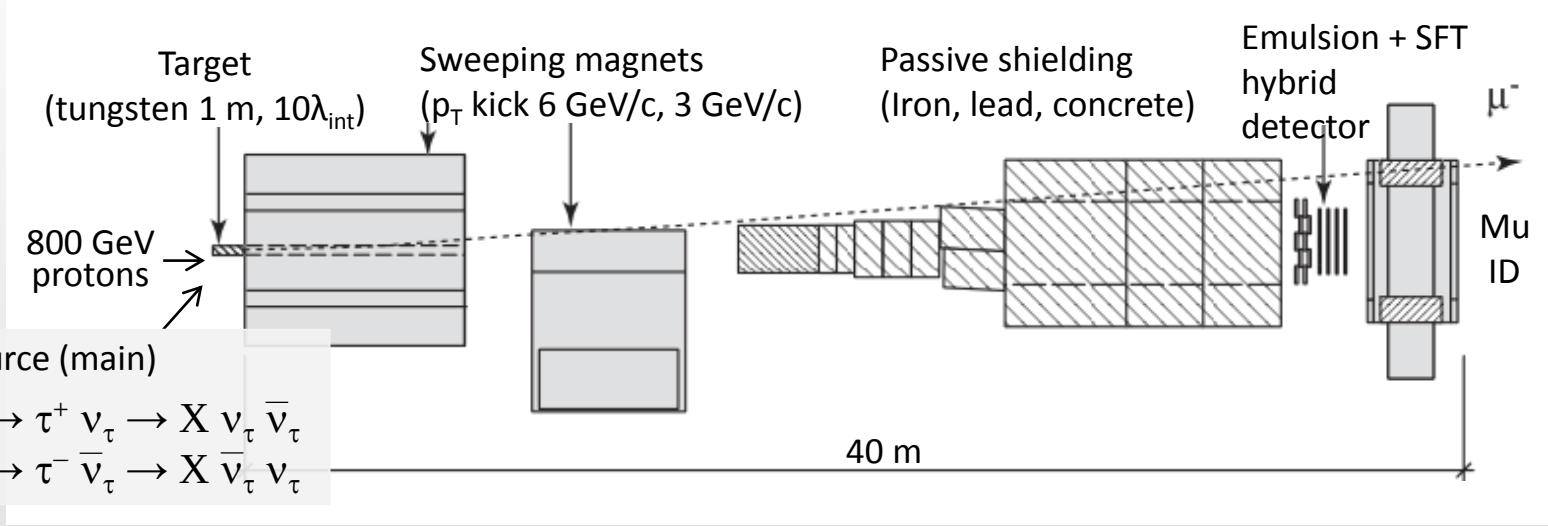






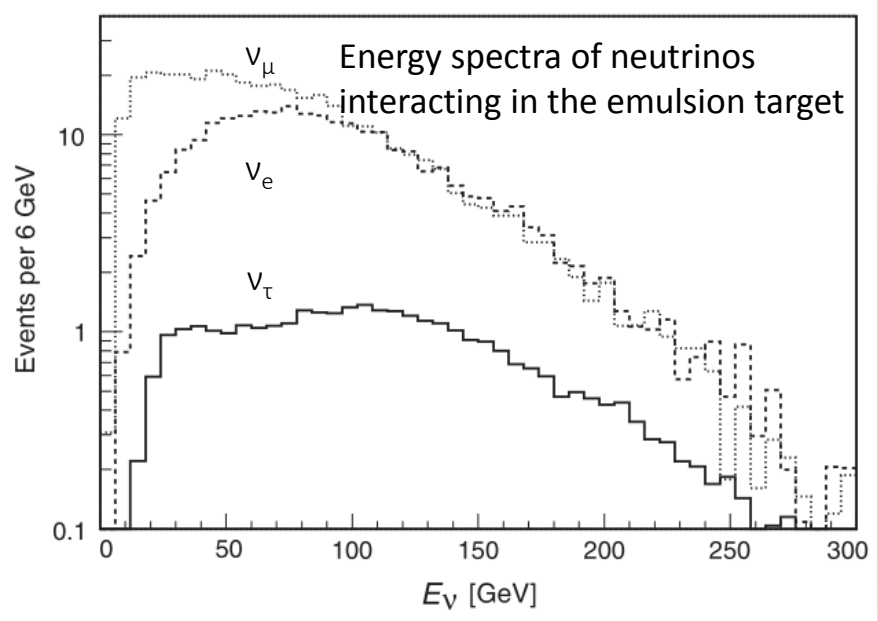
- Angular alignment between films to be done by using dense 400 GeV proton tracks

The DONuT experiment (Fermilab E872)

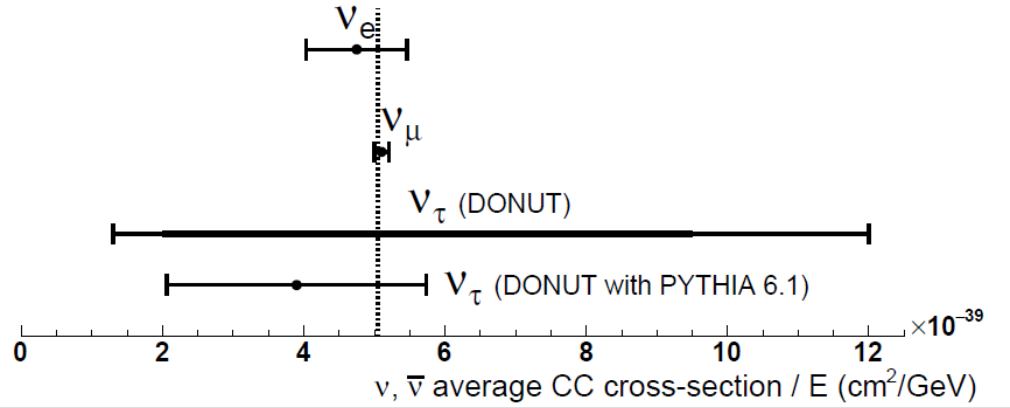


ν_τ source (main)

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



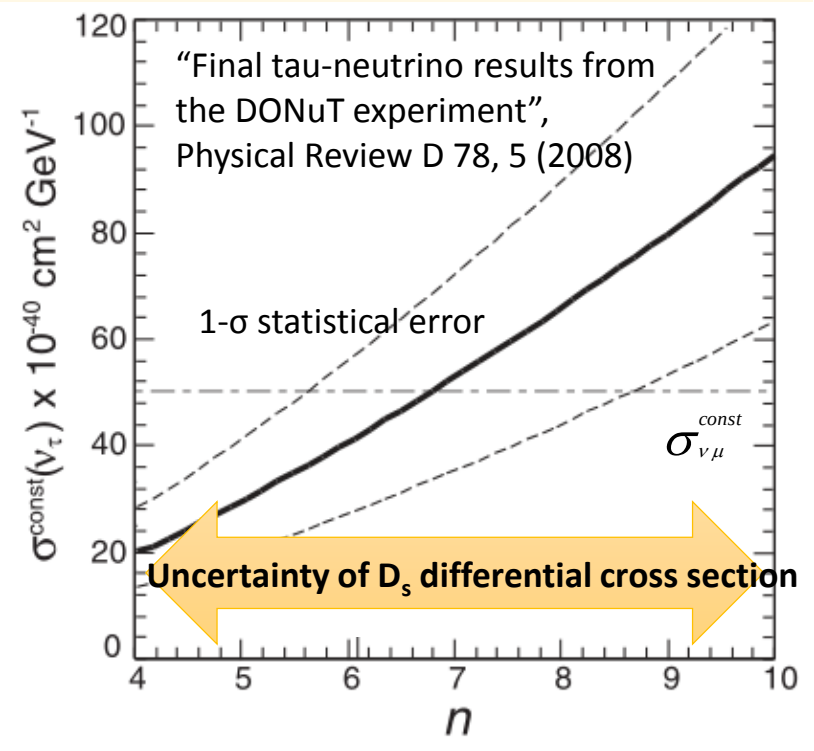
- First direct observation of ν_τ interactions
- 9 ν_τ CC events observed with an estimated background of 1.5 events



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



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

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

Parametrization used in DONUT

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

No experimental result effectively constraining the D_s differential cross section

The energy-independent part was parameterized as

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

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**

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 ± 2.0 b(D) = 0.8 ± 0.2
E781 (SELEX)	Σ^- (sdd) / 600					~350 D_s^- events, ~130 D_s^+ events ($x_F > 0.15$) $n(D_s^-) = 4.1 \pm 0.3$ (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

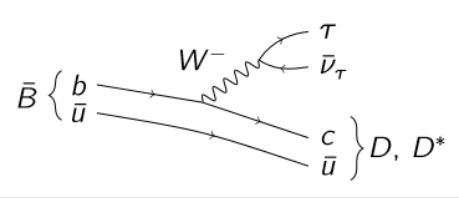
	DsTau	SHiP charm (SPSC-EOI-017)
structure	**Thin target** + decay volume	**ECC** with sliced replica target + magnet + muID
Target	Tungsten / Molybdenum	TZM
Emulsion film area	593 m^2	20 m^2 – 60 m^2
# of modules (runs)	368	40 – 120
pot	4.6 x 10^9	2 x 10^7
# of interactions	2.3 x 10^8	? O(10^7)
Charm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

Indication of possible non-universality?

- W decays (LEP combination)

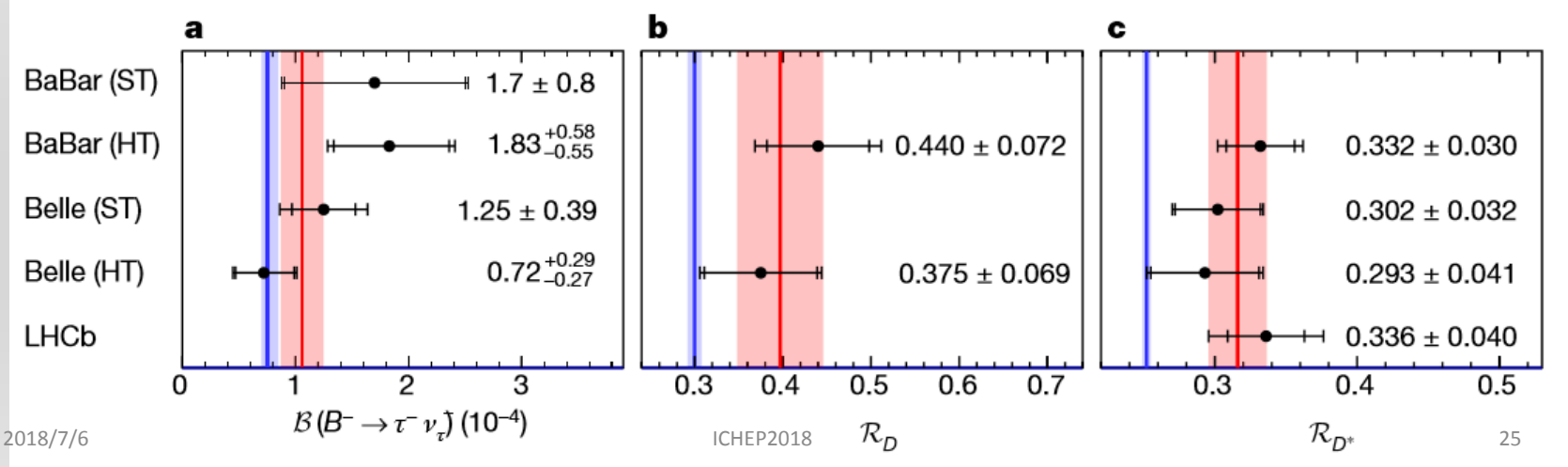
$$\mathcal{B}(W \to \mu\nu_\mu)/\mathcal{B}(W \to e\nu_e) = 0.994 \pm 0.020$$

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



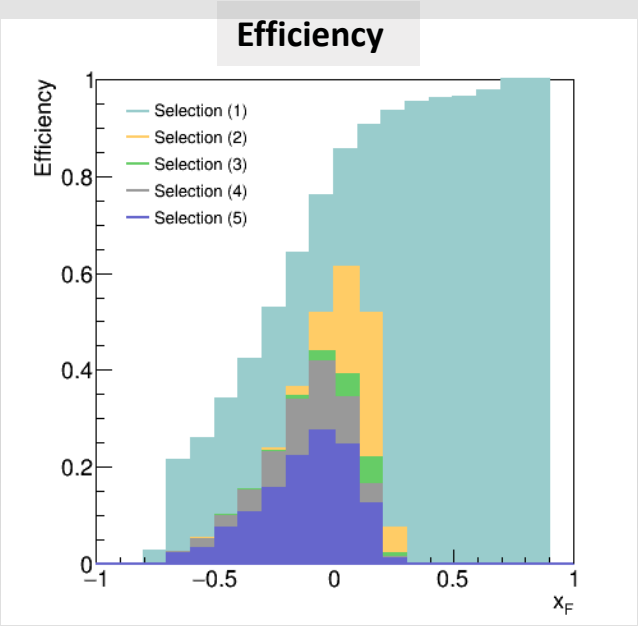
- B-meson decays Nature 546 (2017) 227-233

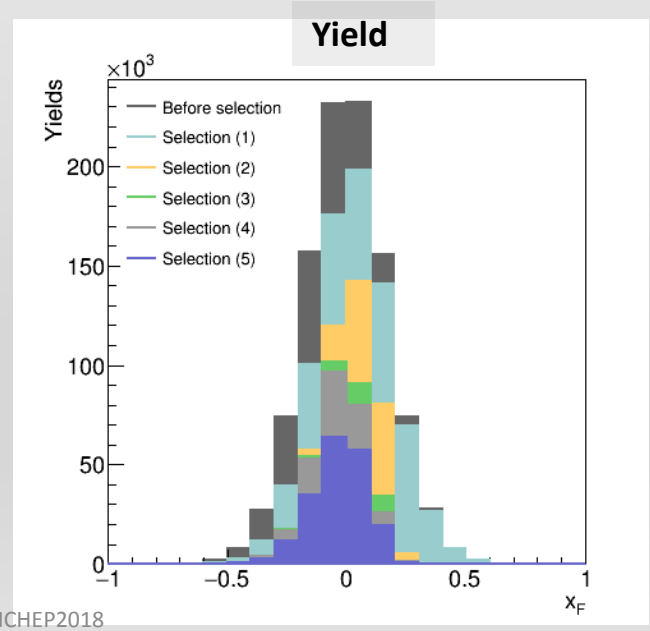
$$\mathcal{B}(B \to \tau\bar{\nu}_\tau) \qquad R_D = \mathcal{B}(\bar{B} \to D\tau\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D\mu\bar{\nu}_\mu)$$



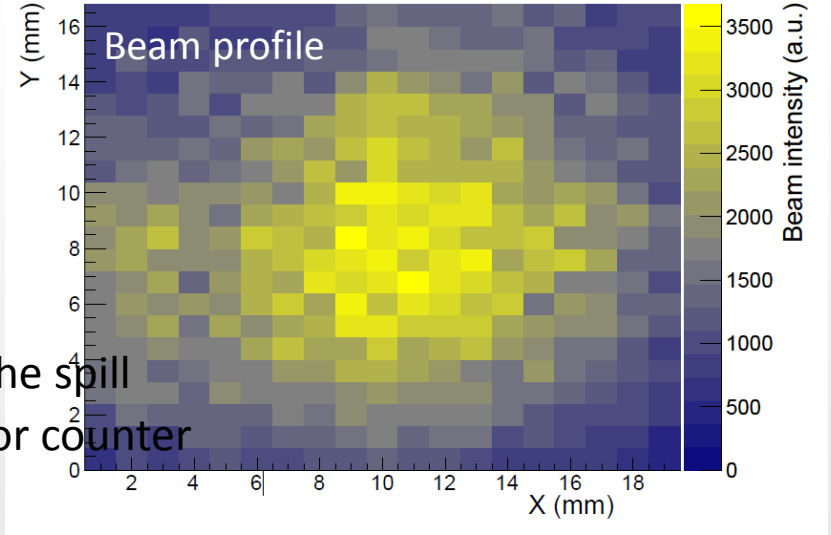
Efficiency of Ds → τ → X detection

Selection	Total 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



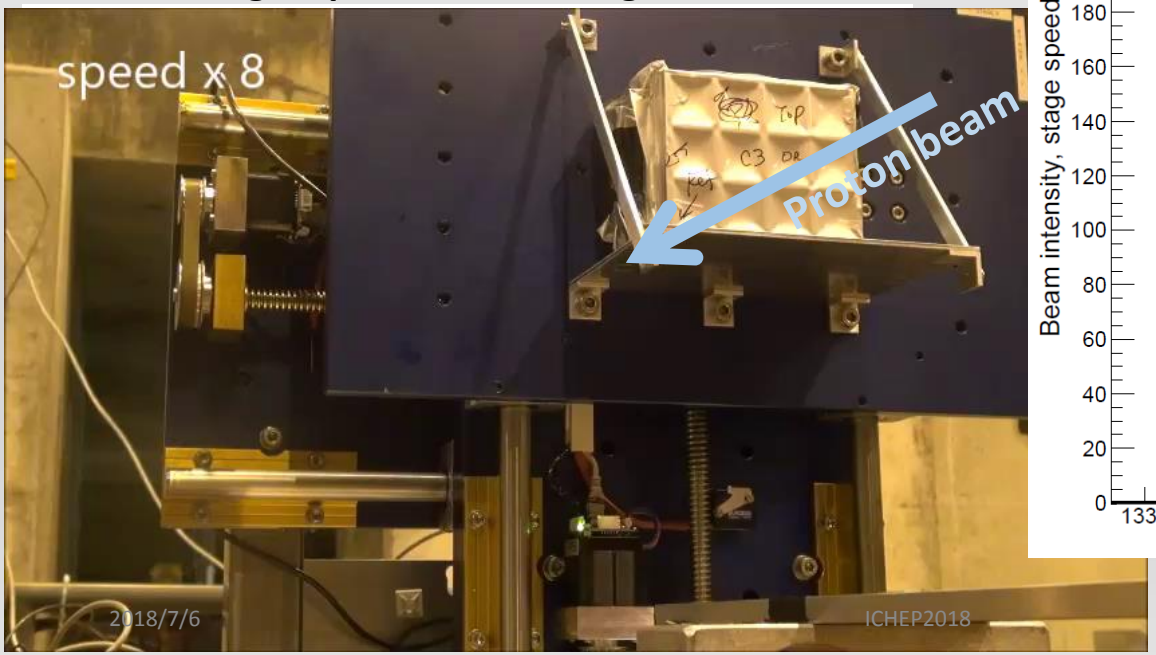


Exposure scheme



- 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