Study of tau-neutrino production at the CERN SPS (CERN-NA65)

Osamu Sato (Nagoya University)
for the DsTau Collaboration

Collaboration

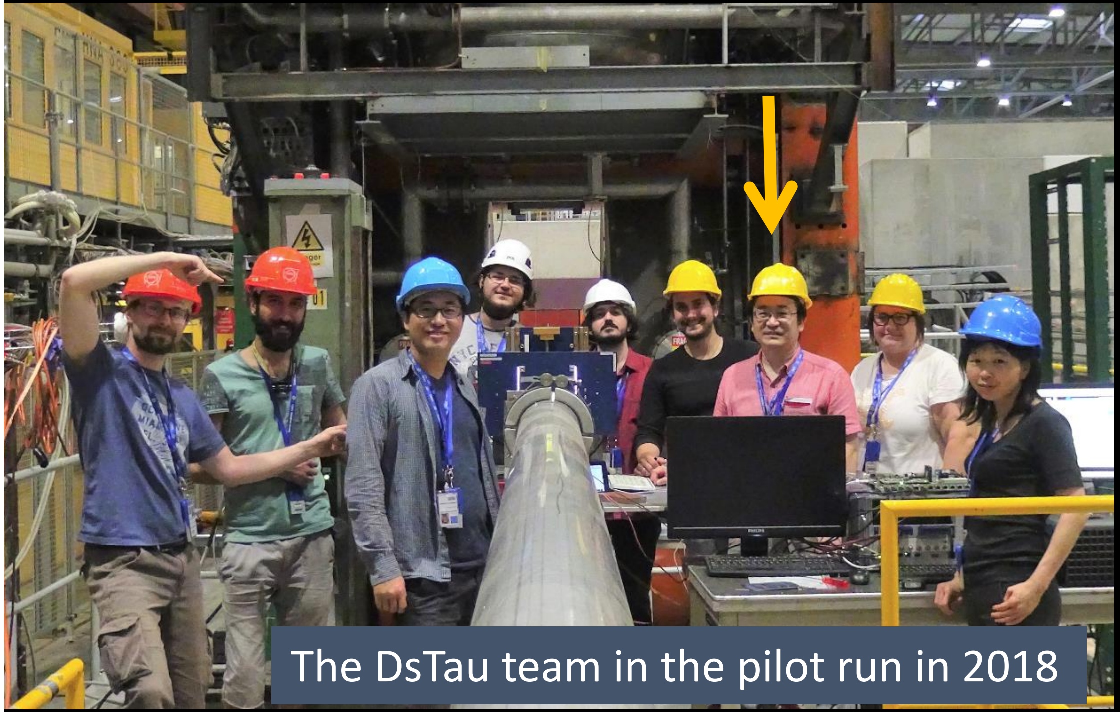
Japan
- Aichi University of Education
- Gifu University
- JAEA-Japan Atomic Energy Agency
- Kobe University
- Kyusyu University
- Nagoya University

Romania
- Institute of Space Science Bucharest

Russia
- JINR-Joint Institute for Nuclear Research

Switzerland
- CERN
- University of Bern

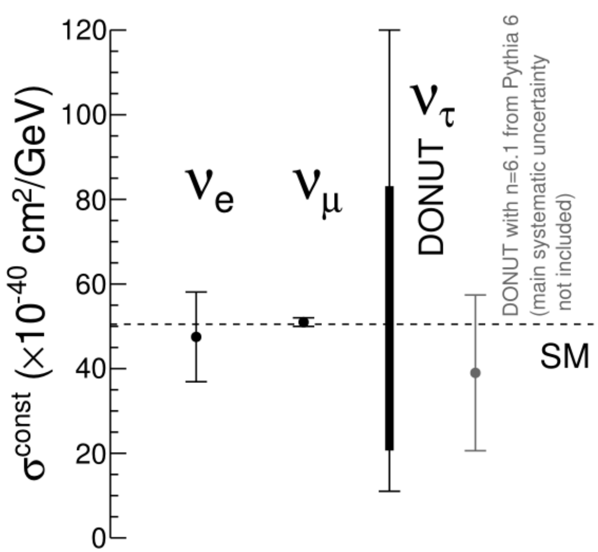
Turkey
- METU-Middle East Technical University



The DsTau team in the pilot run in 2018

Tau neutrinos & lepton universality test

- Tau neutrino is one of the least studied particles
  - Only a few measurements   Direct ν_τ beam: **DONUT** (DIS)
    Oscillated ν_τ: **OPERA** (DIS), **Super-K** (QE), **IceCube** (DIS).
  - cross section error >50% (DIS) due to systematic uncertainty in ν_τ production
- Lepton Universality test in neutrino scattering
  - Hints of 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



Tau neutrino cross-section uncertainties in DONUT

- Tau neutrino **detection** statistics of 9 events, **33%** → SHiP etc
- Tau neutrino **production**: Lack of Ds differential prod cross section data, **>50%** → DsTau
- Tau neutrino **production** : Others, **33%** → DsTau

Need to improve both ν_τ statistics and ν_τ production

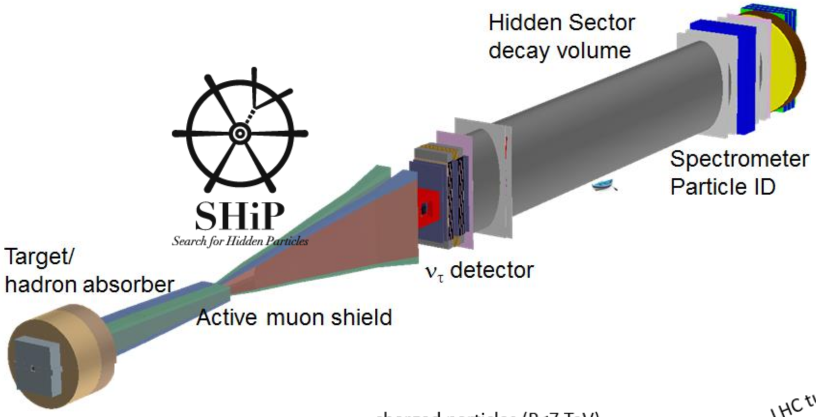
Future tau neutrino measurements

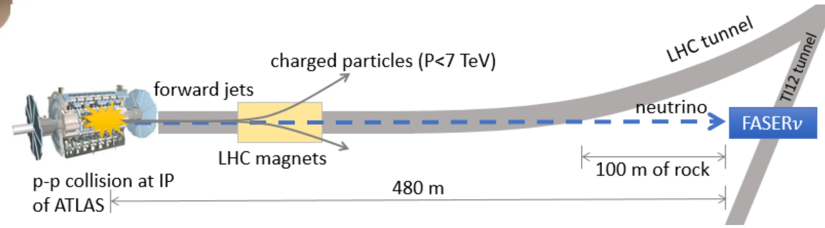
Opportunities to measure ν_τ cross section

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

  δσ ~10% with **DsTau reduction of ν_τ beam uncertainty**

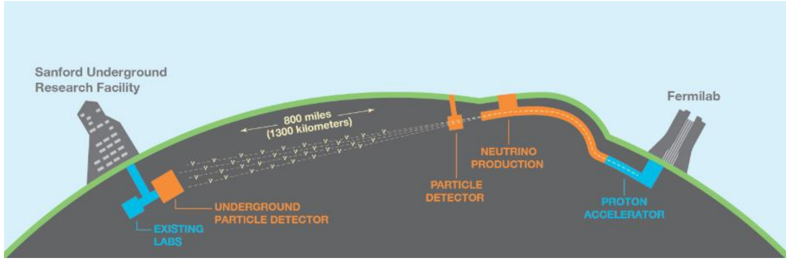
- **FASER**: high energy ν_τ measurements at the LHC.3

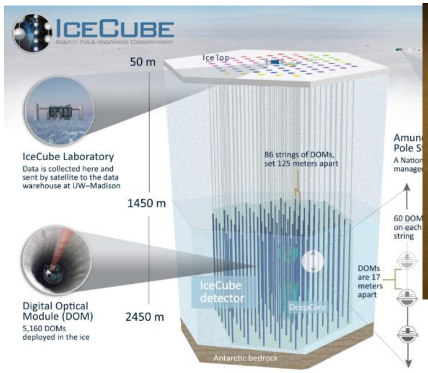


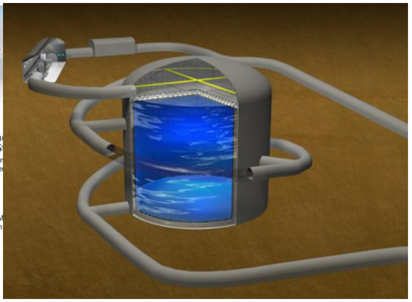


ν_τ cross section has influence to

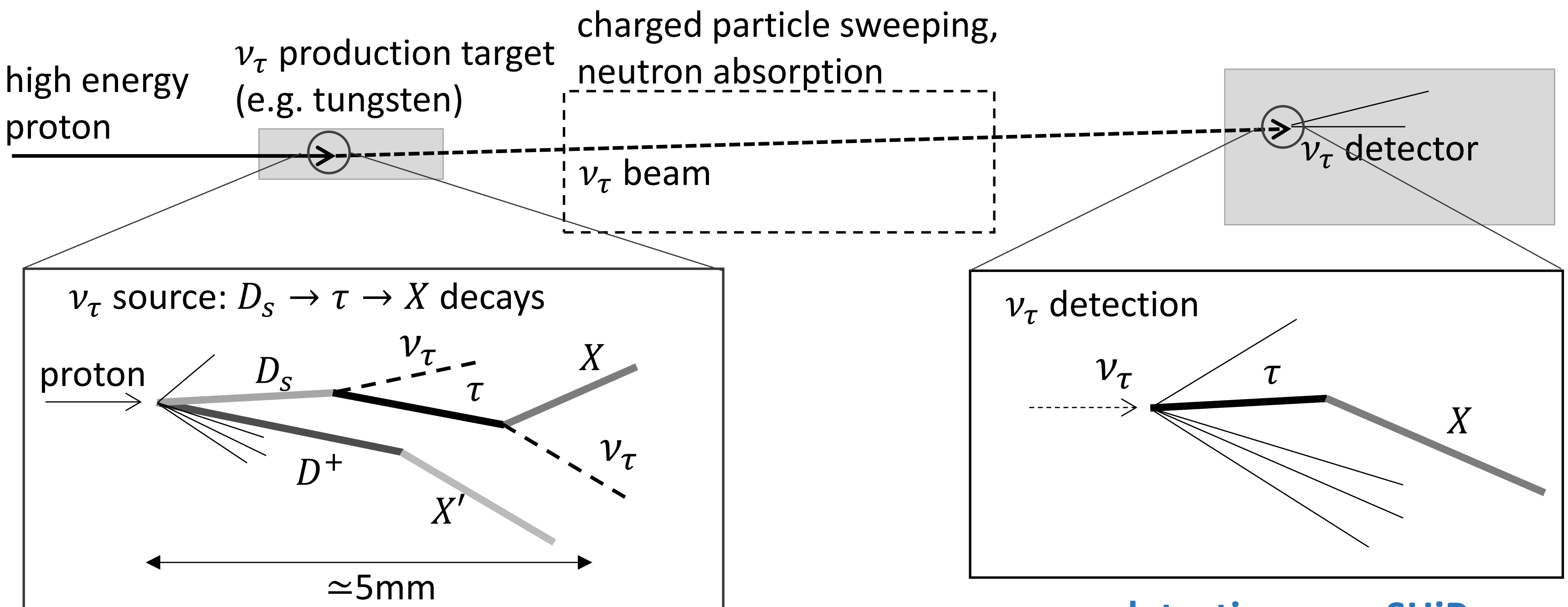
- Long baseline neutrino oscillation experiments
  - **DUNE**, **Hyper-K**, **SK**
  - ν_τ is background to ν_e, due to $\tau \rightarrow e$
- **IceCube**
  - Astrophysical ν_τ measurement







Concept of ν_τ cross section measurement (accelerator based)



ν_τ production study: DsTau

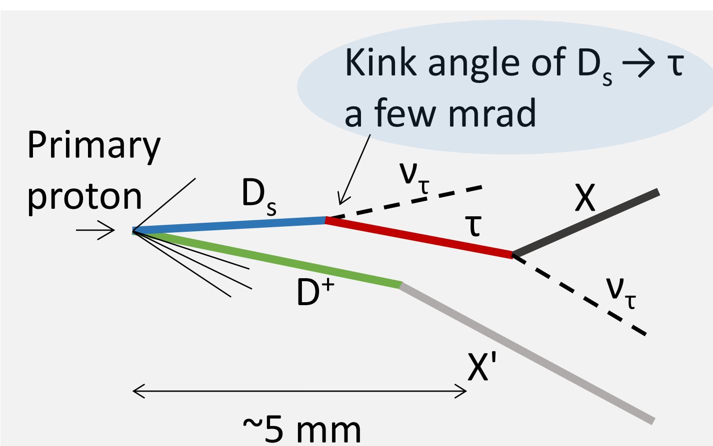
- No experimental data on the Ds differential cross section
- Large systematic uncertainty **(~50%)** in the ν_τ flux prediction

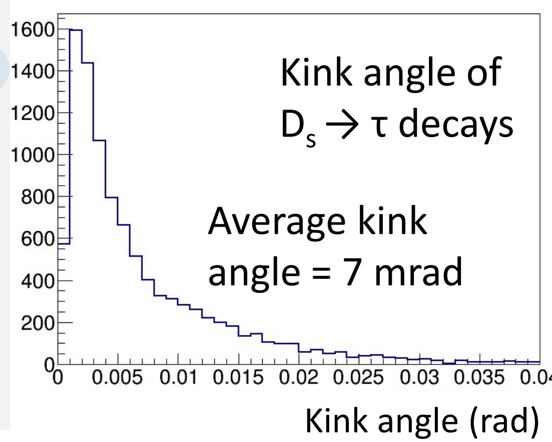
ν_τ detection: e.g. SHiP

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

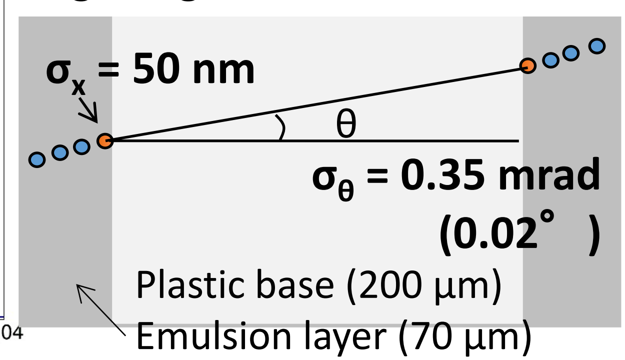
The DsTau project (CERN NA65)

- **Goals:** Study of ν_τ production for future tau neutrino experiments.
  - First measurement of D_s double differential production cross section
  - To reduce uncertainty of ν_τ flux from >50% to 10%.
    - Fundamental input for future ν_τ experiment: SHiP.
  - Byproduct: charm physics, intrinsic charm component in proton.
- **Principle of the experiment**
  - Detection of "**double-kink + charm decay**" topology within some mm.
  - 4.6×10^9 protons, 2.3×10^8 proton interactions in tungsten, 10^5 charm pairs, **$1000\ D_s \to \tau \to X$ decays**.





Emulsion detector:
High angular resolution tracker



Emulsion detector

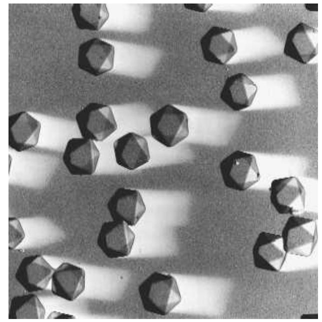
Nucl. Instrum. Methods A 556 80 (2006)

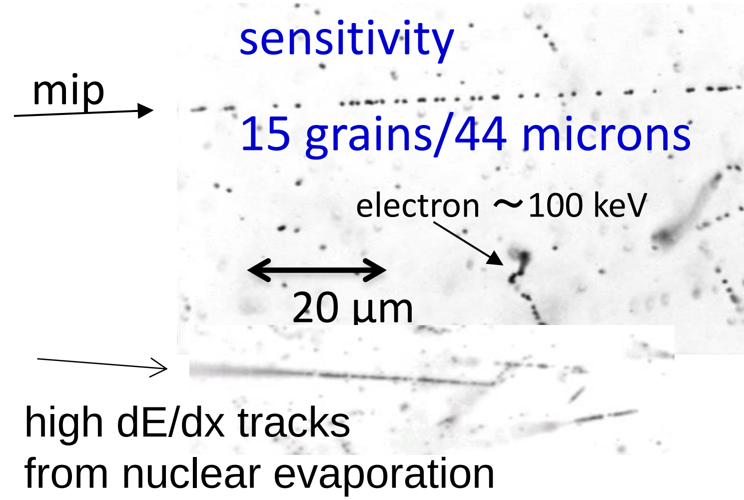
A minimal detector:

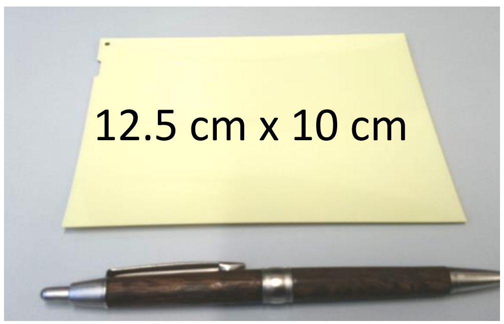
Silverbromide (AgBr) Cristal

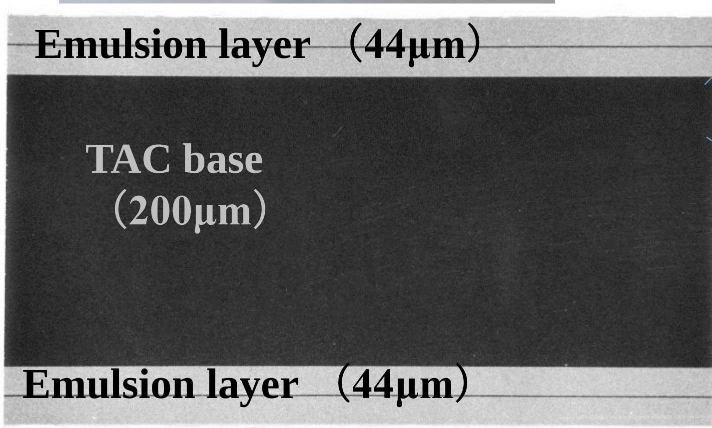
- diameter = 200 nm
- detection eff. = 0.16/crystal
- volume occupancy = 30%

10^{14} crystals in a film

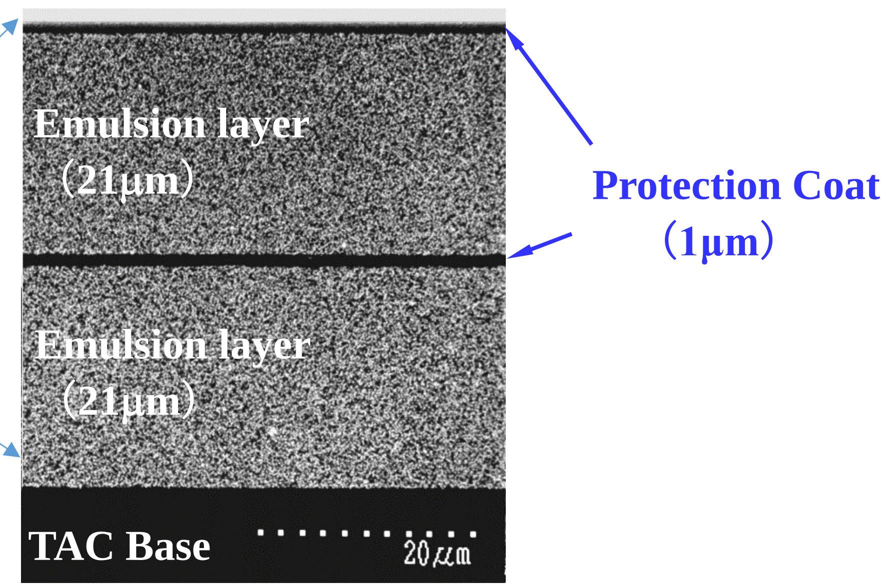




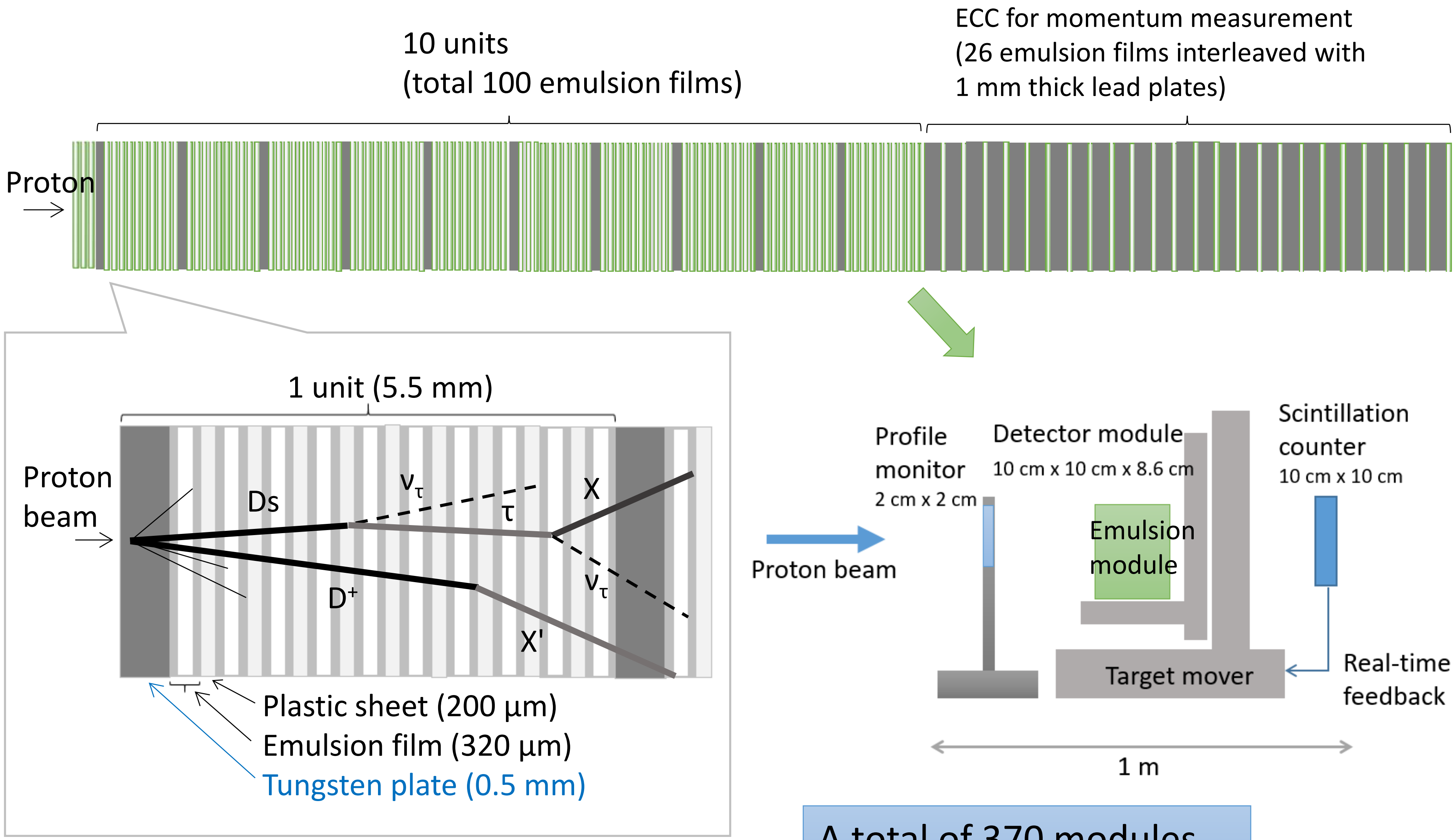




Zoom

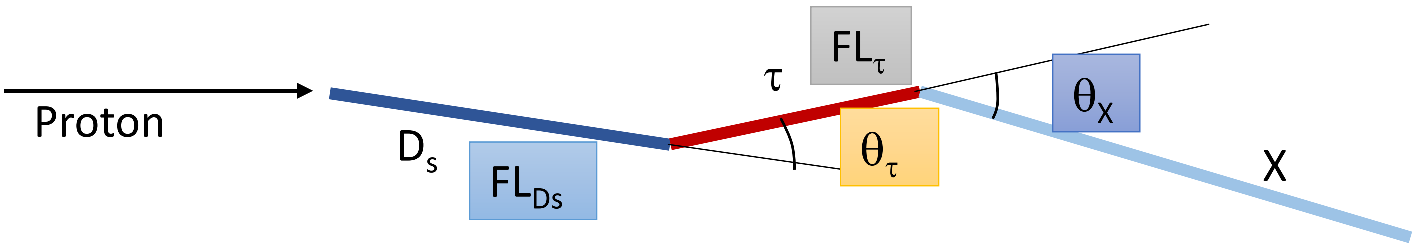


Module structure for $D_s \rightarrow \tau \rightarrow X$ measurement



A total of 370 modules
to be analyzed

Ds momentum reconstruction by geometrical variables by Artificial Neural Network



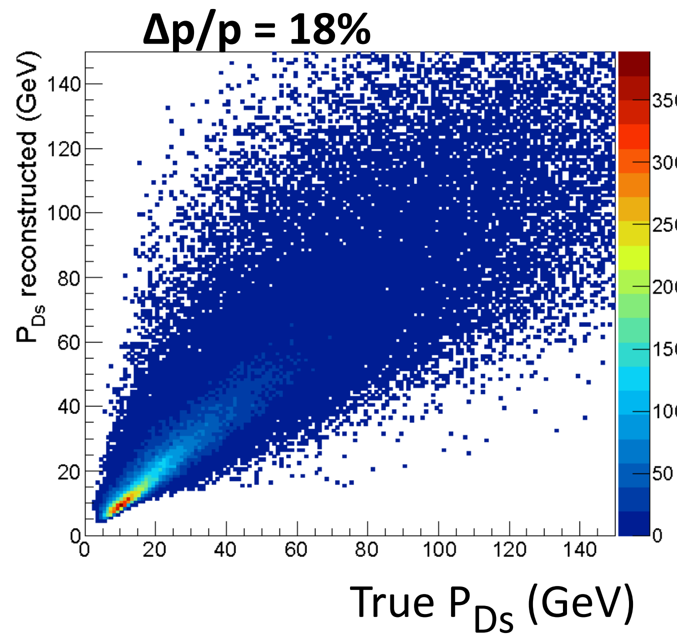
FL: flight length

- 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 $\tau \to 1$ prong decays

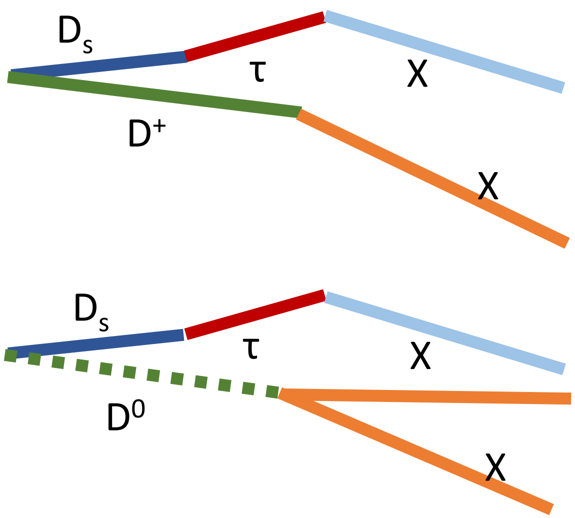
$\Delta p/p = 18\%$



Signal and background

- Signal

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

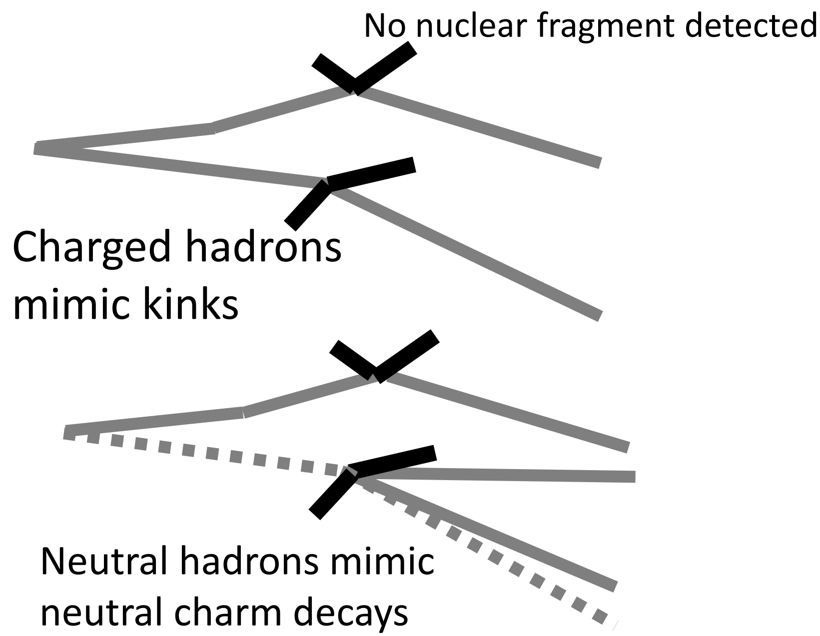


Detection efficiency = 20%, estimated with Pythia 8.

Signal probability 2.2x10^{-7} /proton

Signal in DsTau : 1000

- Main background: Hadron interactions of daughters of proton interactions



Background probability estimated by FLUKA.

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

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

BG in DsTau : 18

DsTau load map

Test beam 2016
- Test of detector structure

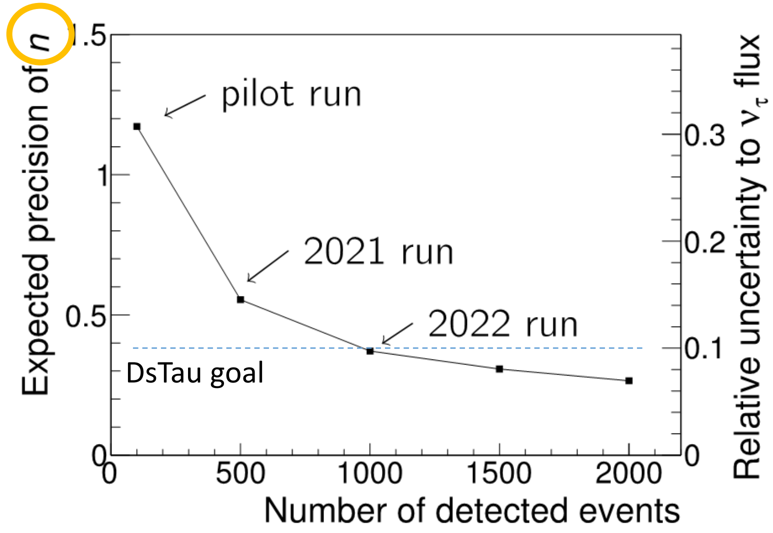
Test beam 2017
- Improved detector structure
- Refine exposure scheme

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

We are here

Physics run 2021-2022
- **Full scale experiment**
- **Aiming at collecting 1000 $D_s \rightarrow \tau \rightarrow X$ events**
- **10 % uncertainty on ν_τ flux**

Approved by CERN Research Board in Jun.2019 as NA65 !



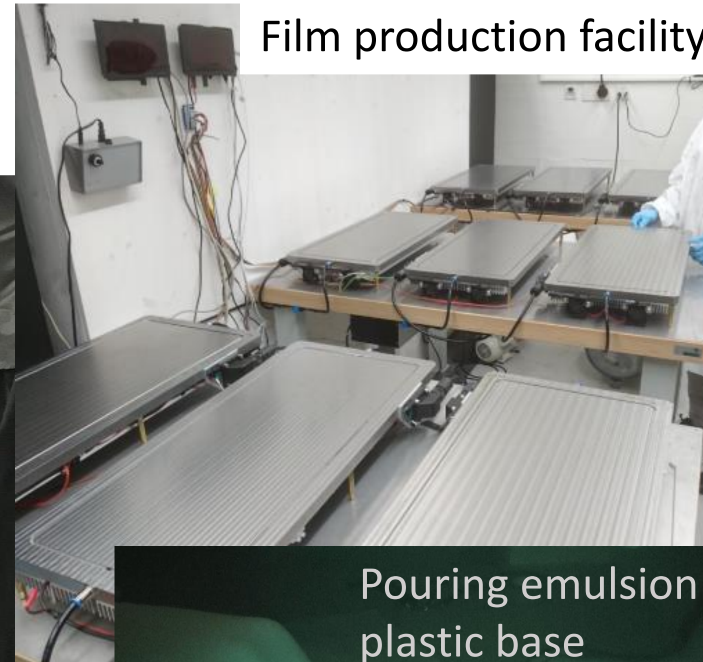
Phenomenological formula

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

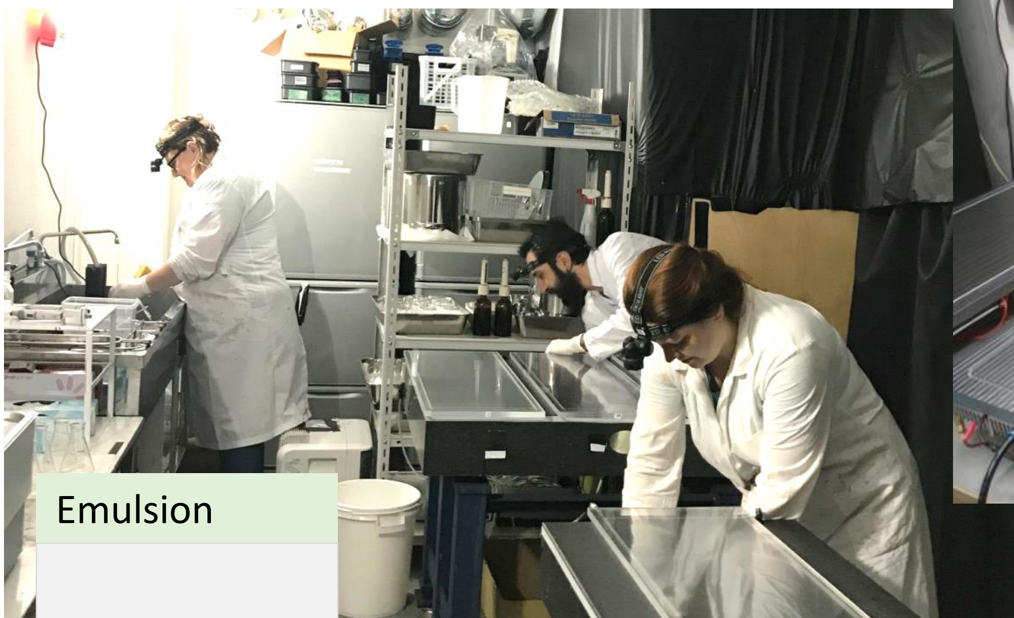
x_F is Feynman x ($x_F = 2p^{CM}_z/\sqrt{s}$) and p_T is transverse momentum

Pilot run: emulsion film production

- 50 m^2 (4000 films) produced
- Film production in Nagoya and Bern in June - August 2018



Film production facility in Bern

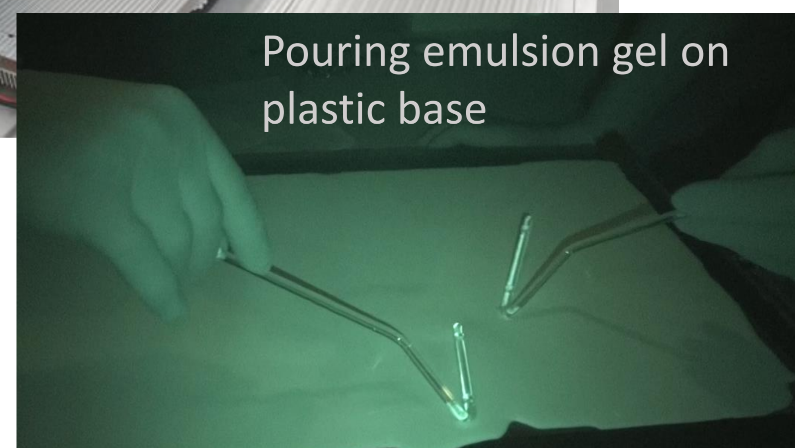


↑ Film production facility in Nagoya

Emulsion

Base

Emulsion

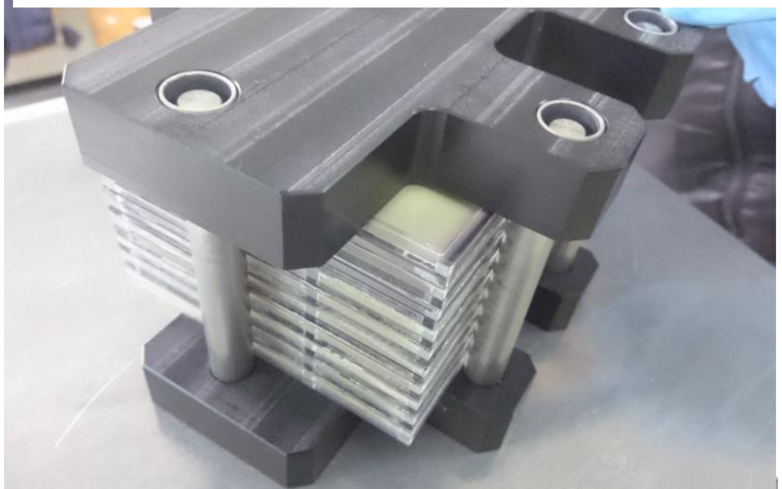


Pouring emulsion gel on plastic base

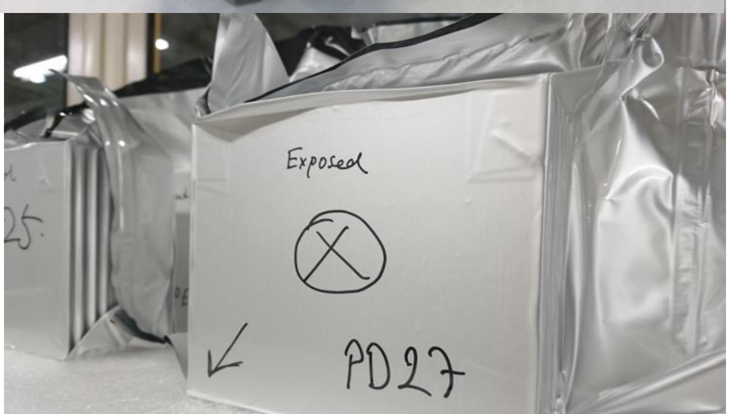
Detector assembling

- 30 modules (131 films/module, 235 components) prepared in total

Mechanical support to assemble modules



A module under assembling in dark

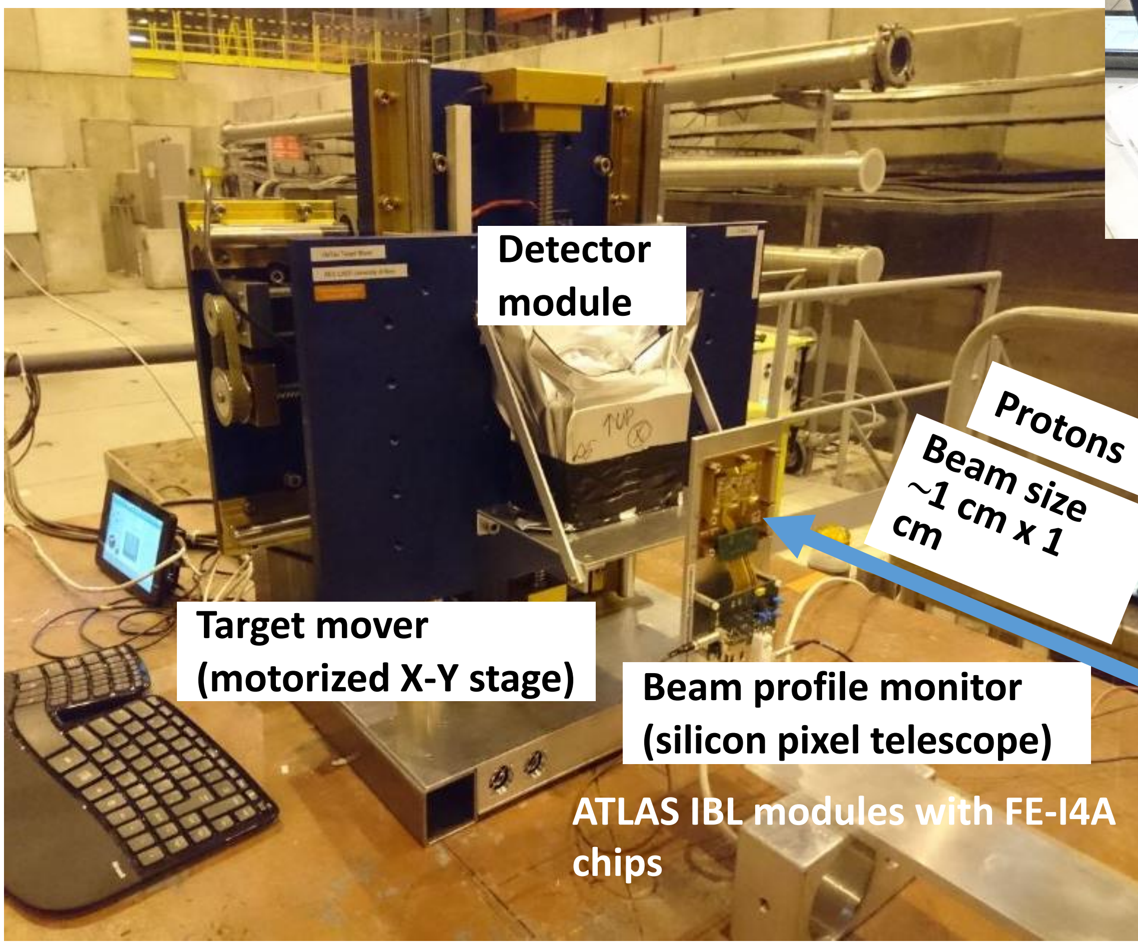


Vacuum packing to hold alignment between films

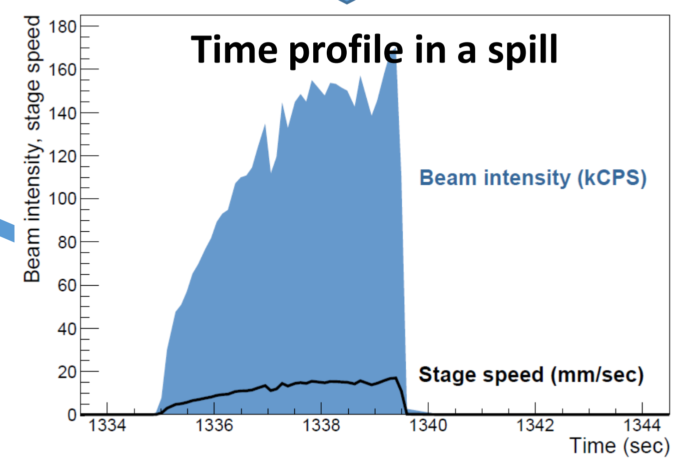
A module on the target mover

Detector setup

Experimental setup at the H4 beamline

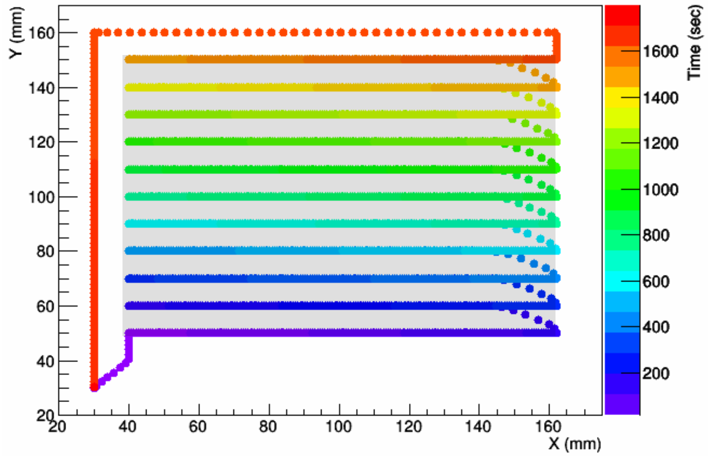


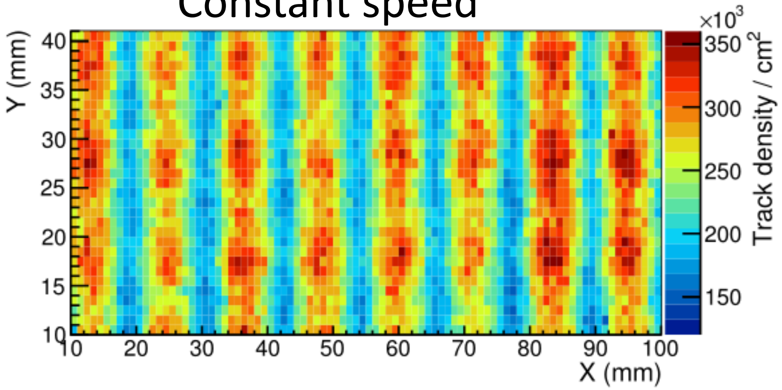
Scintillator for intensity driven control

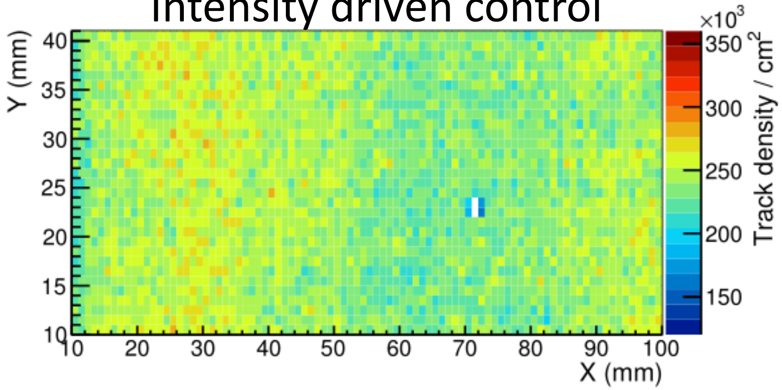


Exposure scheme

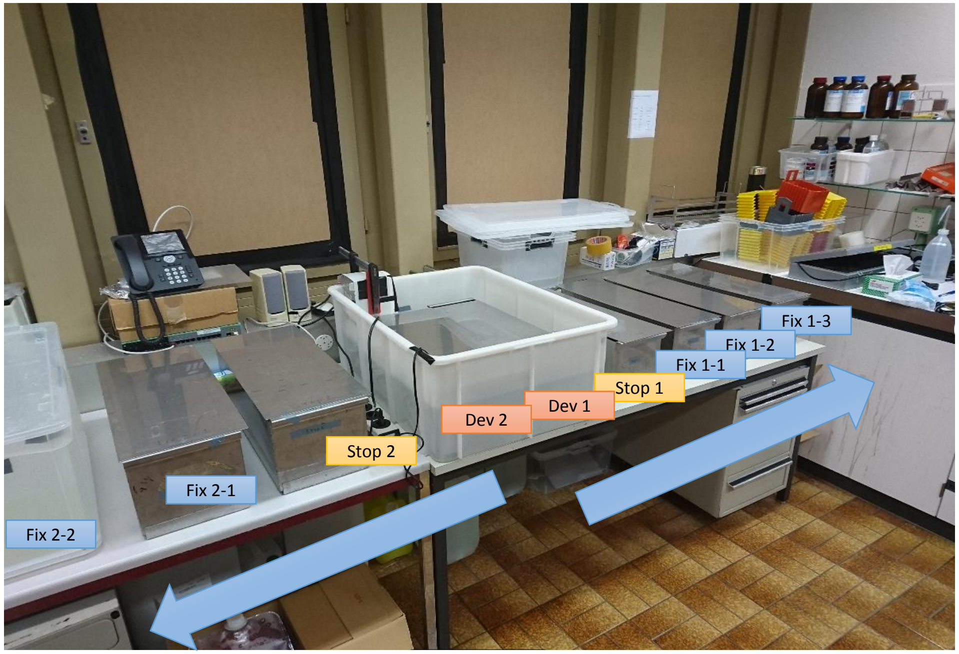
- Target mover (scanning on X)
  - 2016: moved at a constant speed during the spill
  - 2017, 2018: intensity driven control by scintillator counter (feedback each 0.2 sec)
- 10^5 protons / cm^2
- 0.5 - 1 hour per module
- 30 modules exposed in 23rd -27th Aug 2018.

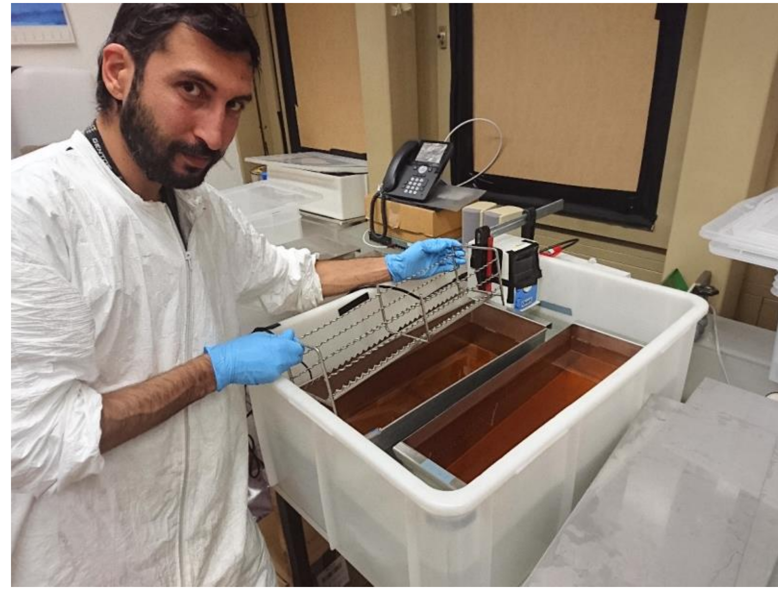






Development in Bern, 8/28-10/4





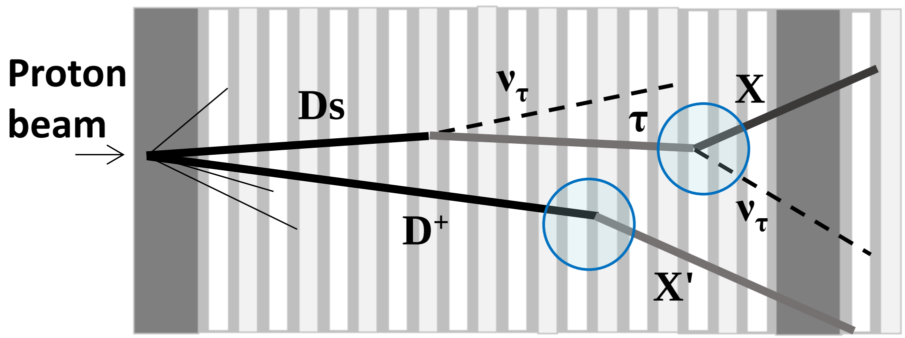
- Total 4000 films
- Tons of chemical were used.

← Developed films

Analysis scheme for double-kink search

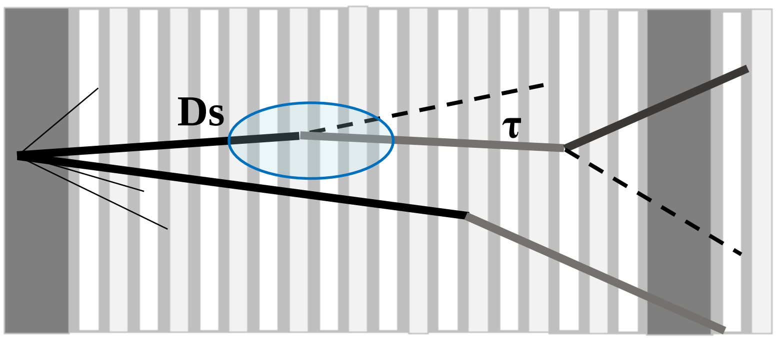
Step 1

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



Step 2

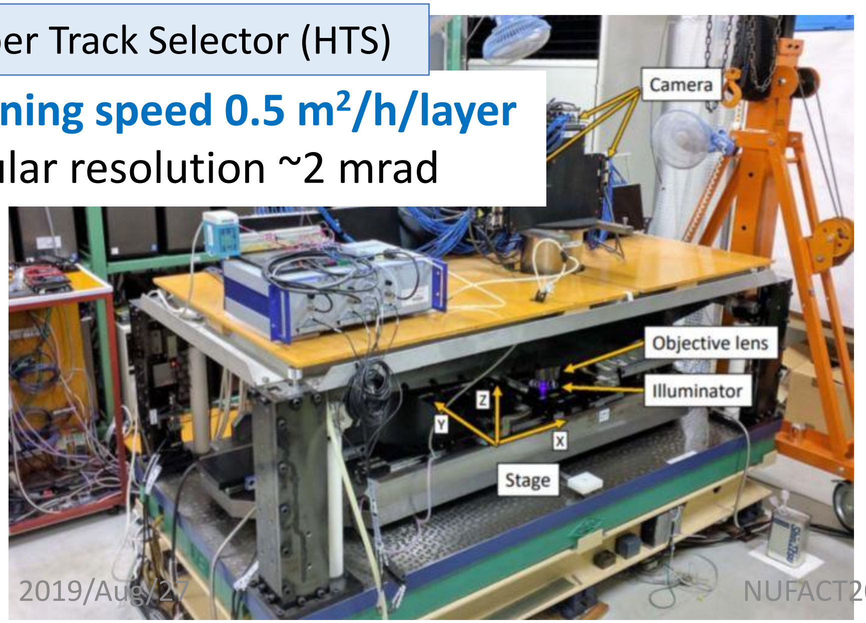
- Precision measurement to detect Ds -> τ decay (a few mrad)



Hyper Track Selector (HTS)

Scanning speed 0.5 m²/h/layer

Angular resolution ~2 mrad

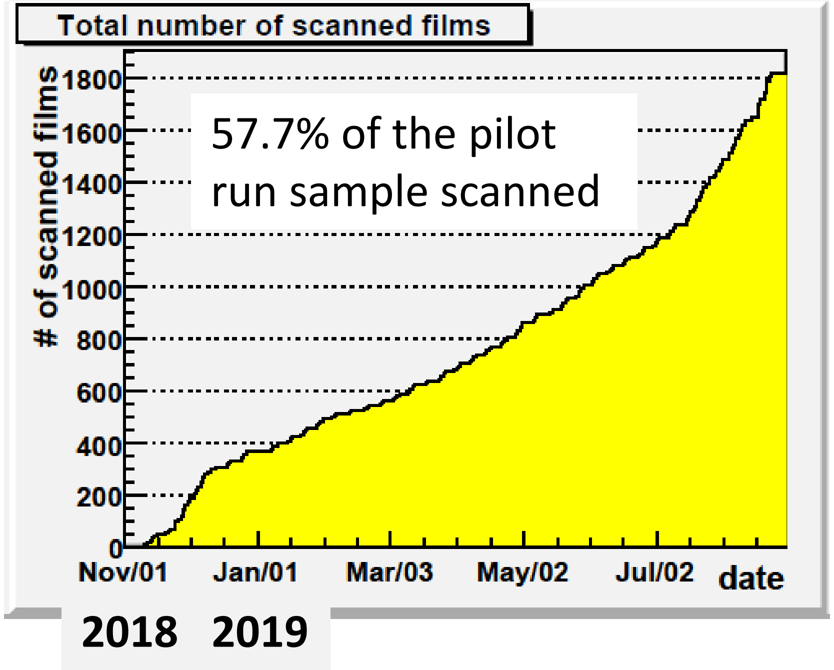


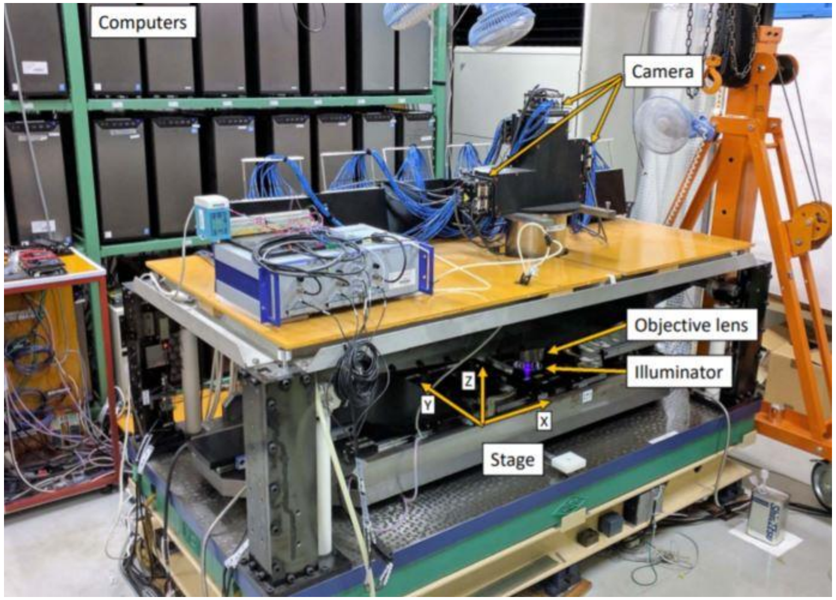
Nano-precision systems

Angular resolution ~0.3 mrad

Status of fast readout by HTS

- **57.7 %** of the pilot run films have been already scanned
  - 1817 out of 3150 films
- Bare scanning speed = 6 min / film
  - ≃10 TB image data/films

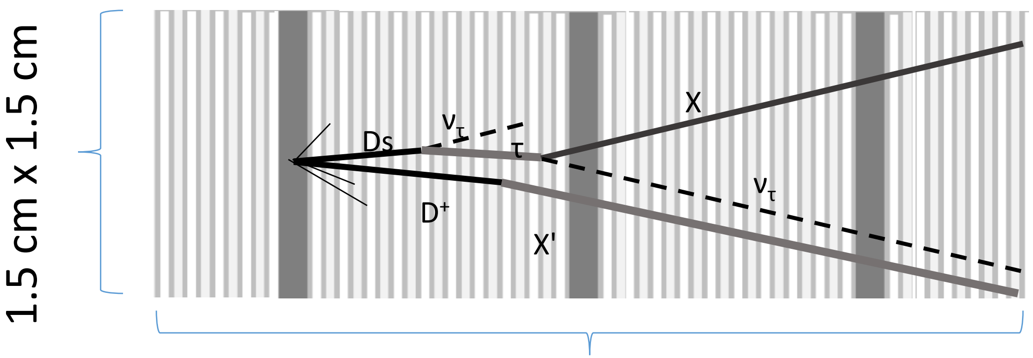




- Prospect: Complete fast readout by the end of 2019

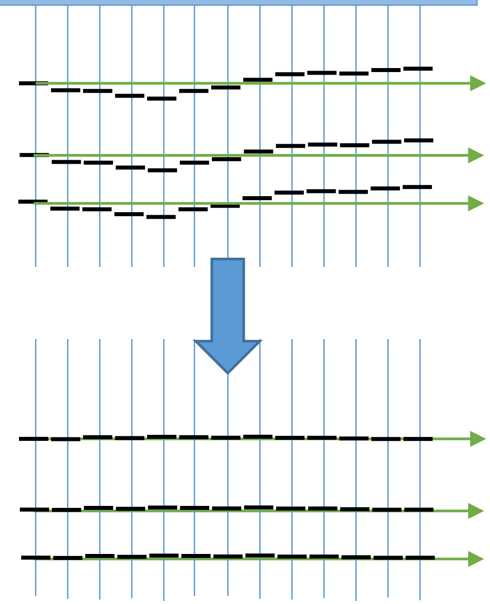
Reconstruction performance (1): alignment

- Processing in sub-volumes
  - e.g. 1.5 cm x 1.5 cm x 30 films
- Alignment with proton beam tracks
  - Alignment accuracy better than **0.4 μm**

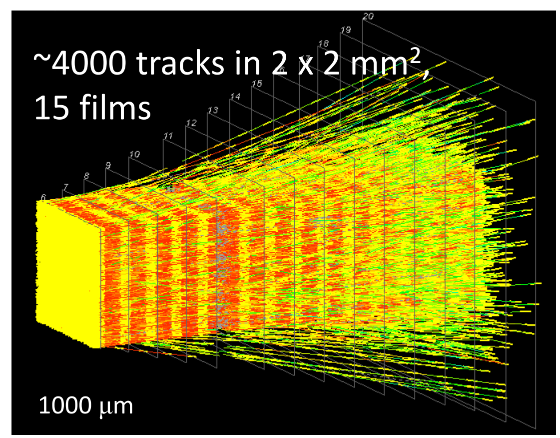


30 films
(two tungsten plates to reject low momentum daughter candidates)

Align films with proton tracks, 100 tracks/mm^2

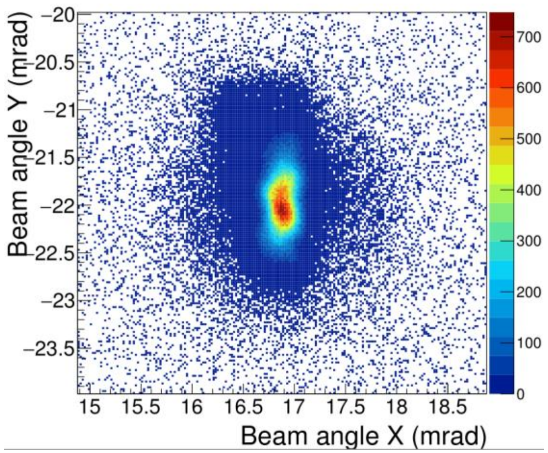


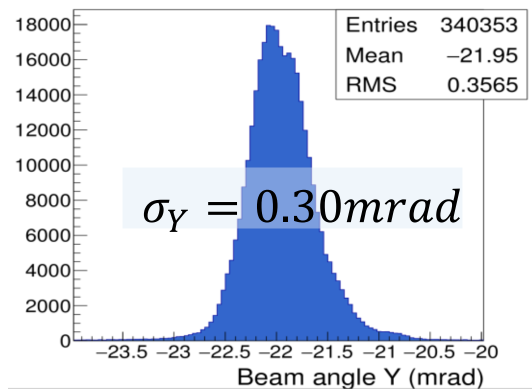
Residual of track segments to fitted line (RMS) $\simeq$**0.4 μm**

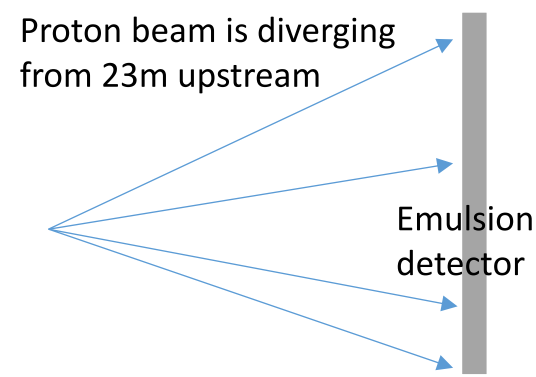


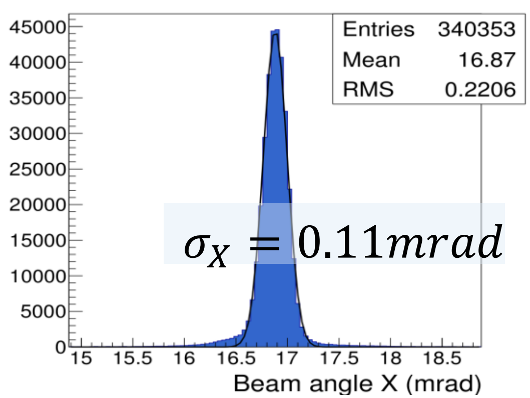
Reconstruction performance (2): Proton beam angle structure

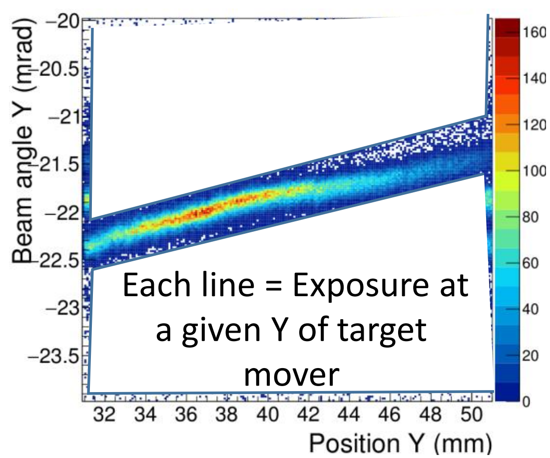
- Proton beam tracks were checked in detail
  - Tracks reconstructed in 20 emulsion films, thickness of 1.1 cm

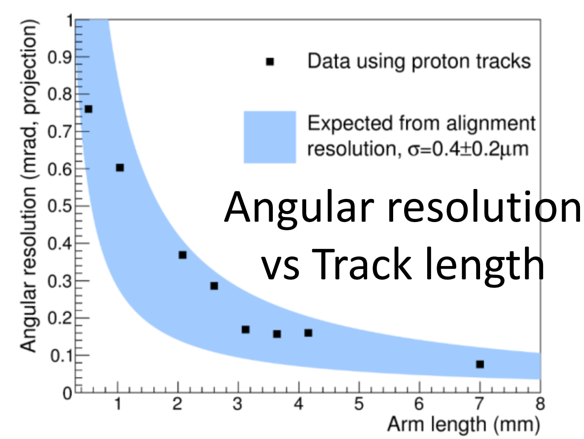






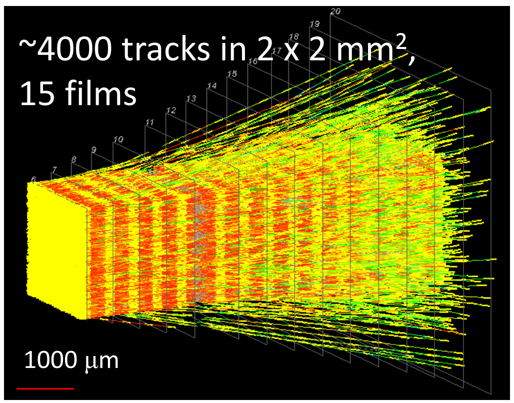


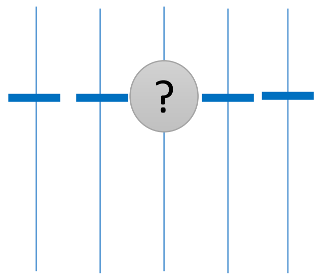


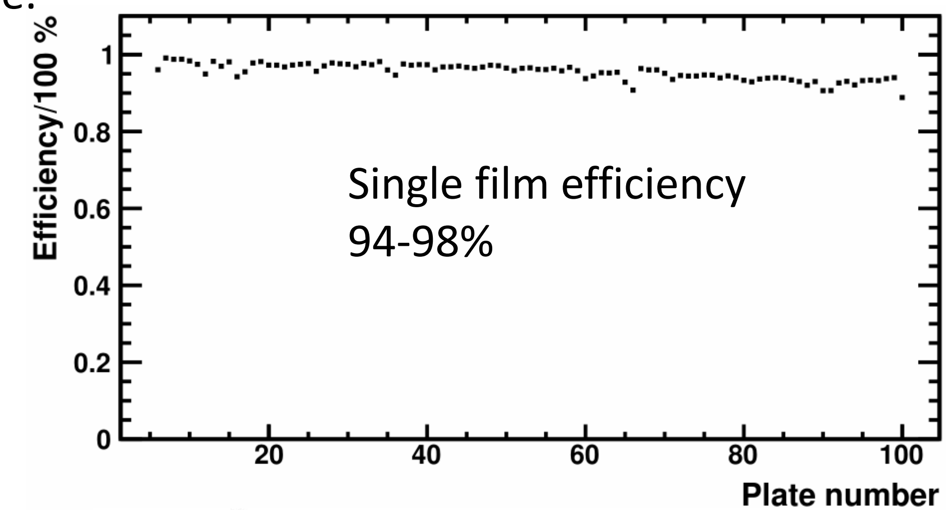


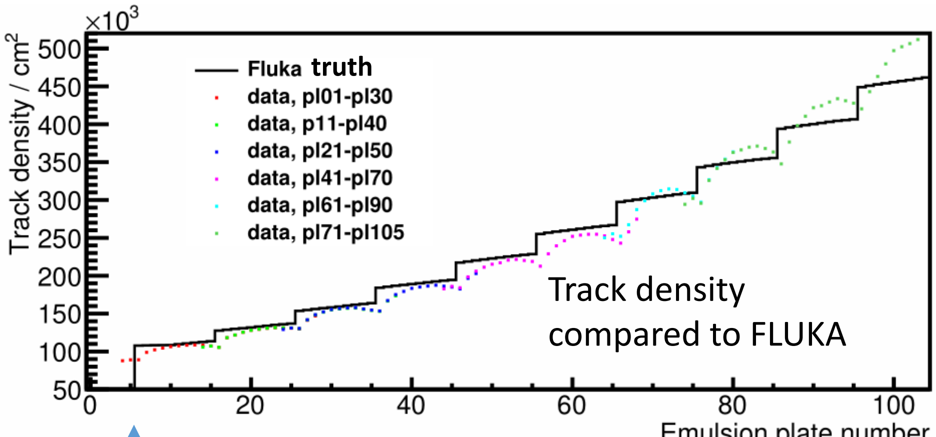
Reconstruction performance (3)
Efficiency, track density

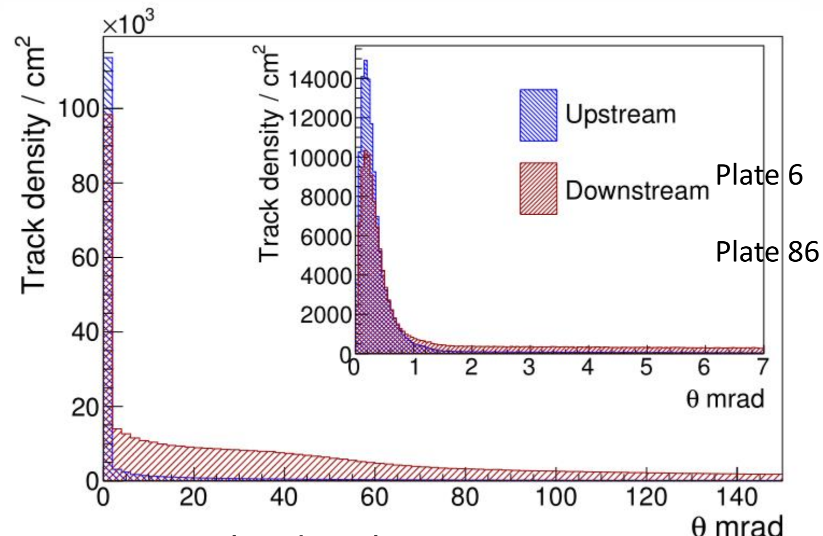
Check of data in the full depth of decay module.
Single film efficiency OK.
Track density evolution matches with FLUKA.







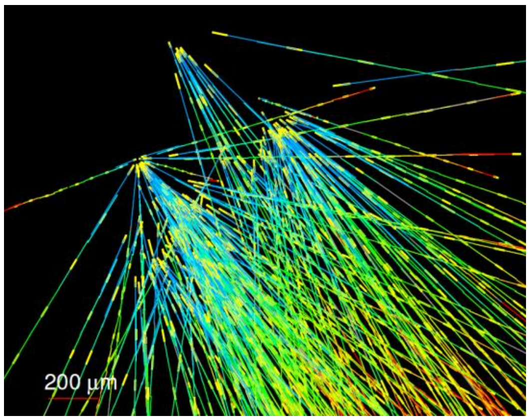




Angular distribution

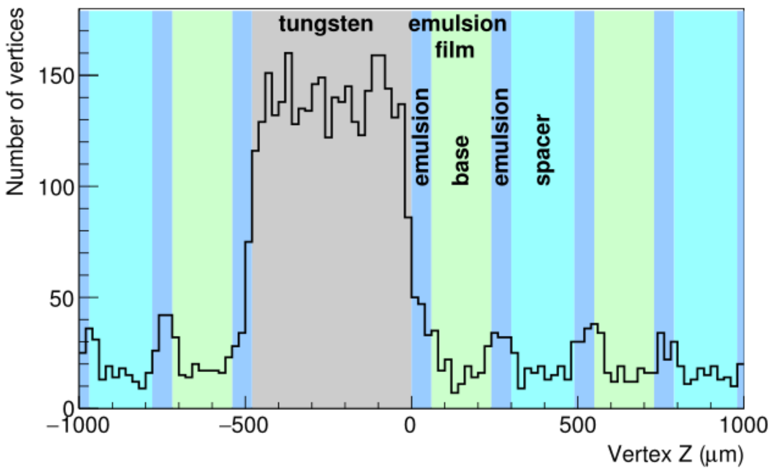
Reconstruction performance (4): Vertexing

Tracks emerging from tungsten target

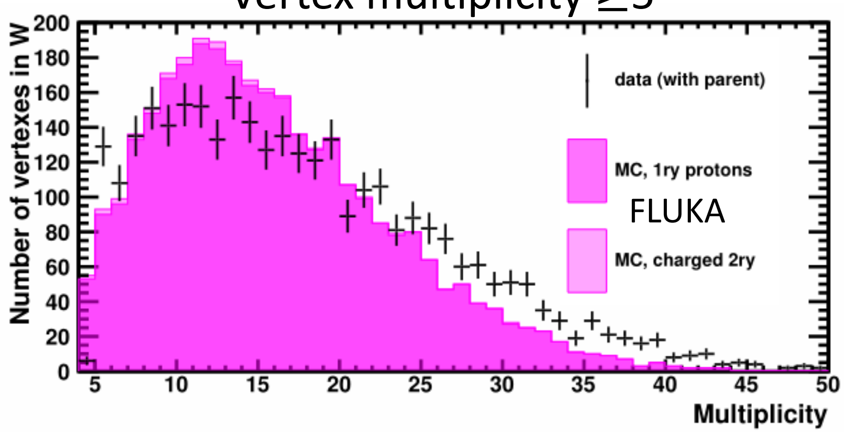


Vertex density 500/cm²

Reconstructed vertex position in



Vertex multiplicity ≥5



Fine detector structure is observed by reconstructed vertices.

We are performing step by step comparison between data/FLUKA

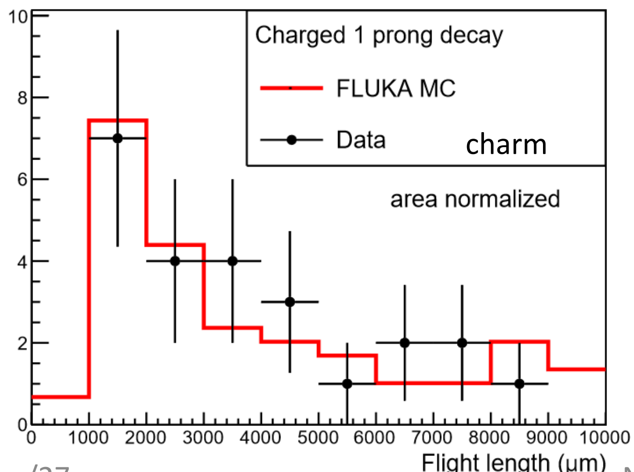
Reconstruction performance (5): Decay search

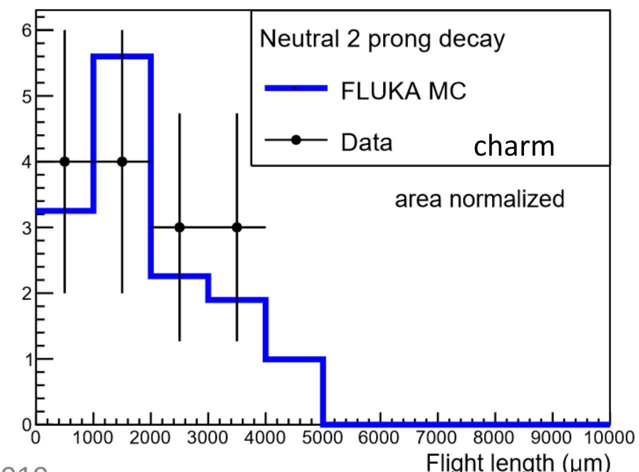
- Subsample of 2016 and 2018 runs were analyzed.
- Double charm event search
  - "A charged 1 prong decay && another charged or neutral decays".

	Subsample in 2016 run		Subsample in the pilot run	
Analyzed protons (normalization)	3712959		3355967	
	Data	Expected	Data	Expected
Vertices in tungsten	19008	18567.2	17001	16779.1
Double decay topology	10	9.1	10	8.2

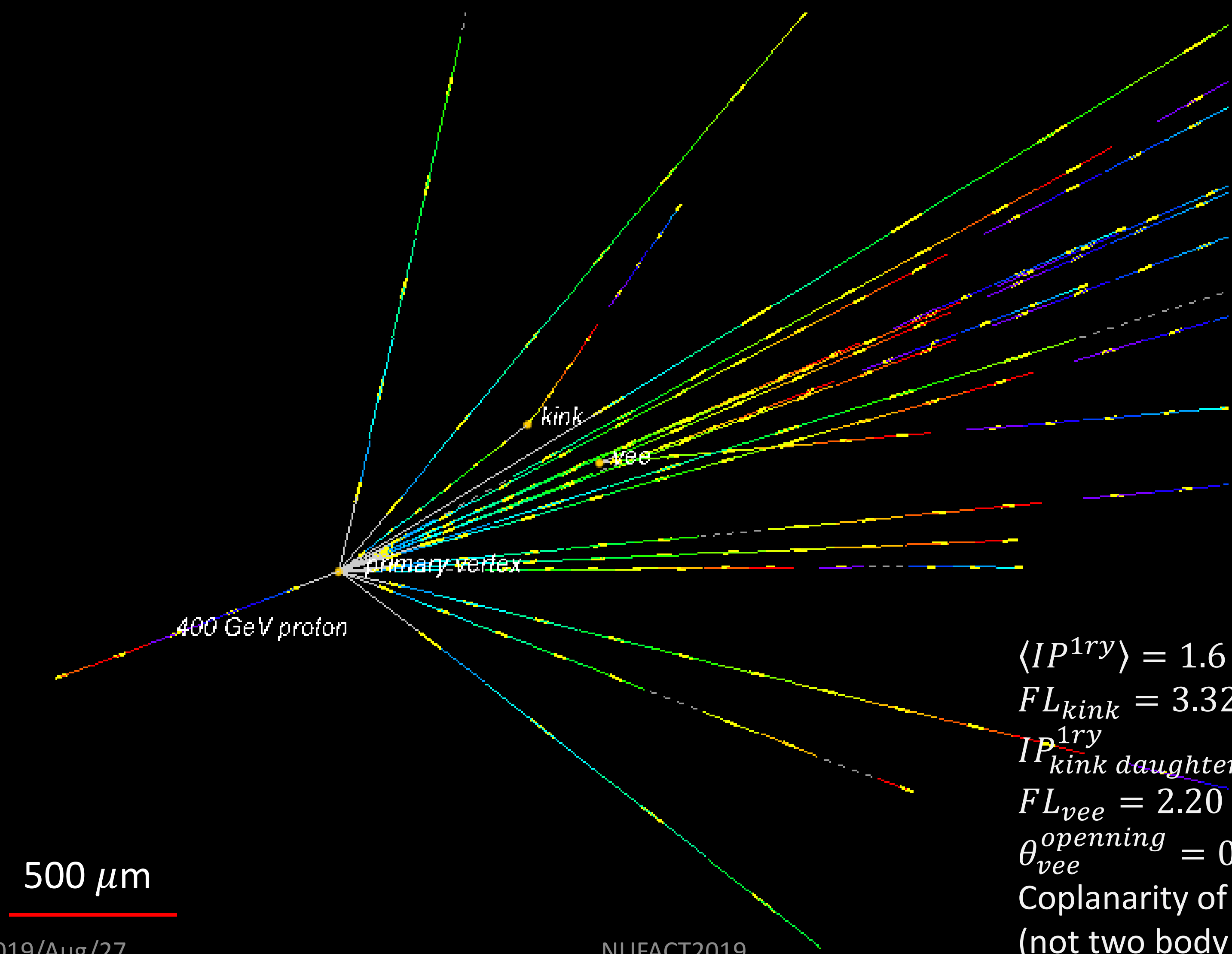
Interactions in single tungsten plate

- Flight length distribution shows **charm analysis chain works**.





A double charm candidate, kink + vee



$\langle IP^{1ry} \rangle$ = 1.6 μm
FL_{kink} = 3.32 mm
$IP^{1ry}_{kink\ daughter}$ = 174 μm
FL_{vee} = 2.20 mm
$\theta^{openning}_{vee}$ = 0.132 rad
Coplanarity of vee = 15.2 mrad
(not two body decay)

Plan for physics runs in 2021, 2022 (NA65)

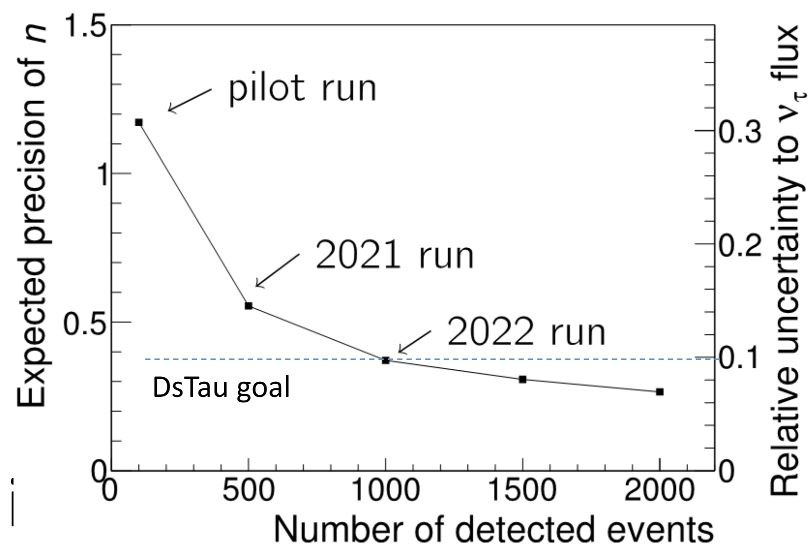
Test beam 2016
- Test of detector structure

Test beam 2017
- Improved detector structure
- Refine exposure scheme

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

Physics run 2021-2022
- Full scale experiment
- Aiming at collecting 1000 $D_s \rightarrow \tau \rightarrow X$ events
- 10 % uncertainty

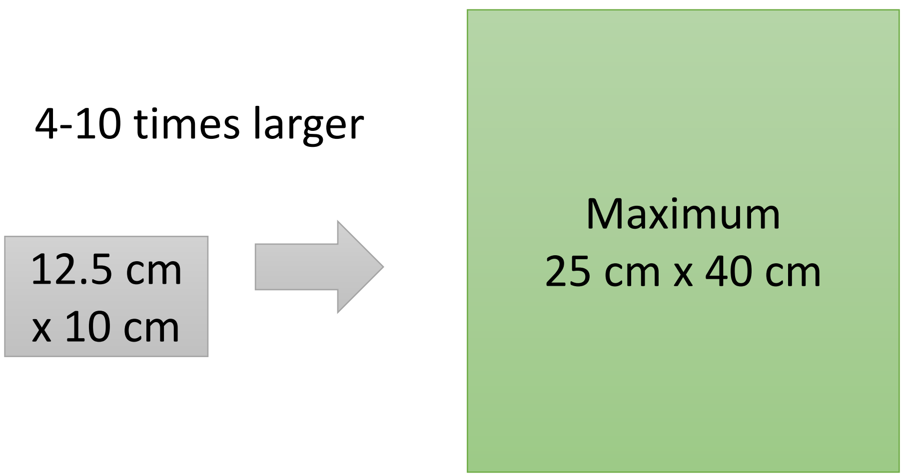
	# of modules	emulsion films (m^2)
Pilot run 2018	30	49
Physics run 2021	**150**	**246**
Physics run 2022	**190**	**312**



- 2 weeks each
- The exposure speed achieved i the pilot run is quick enough

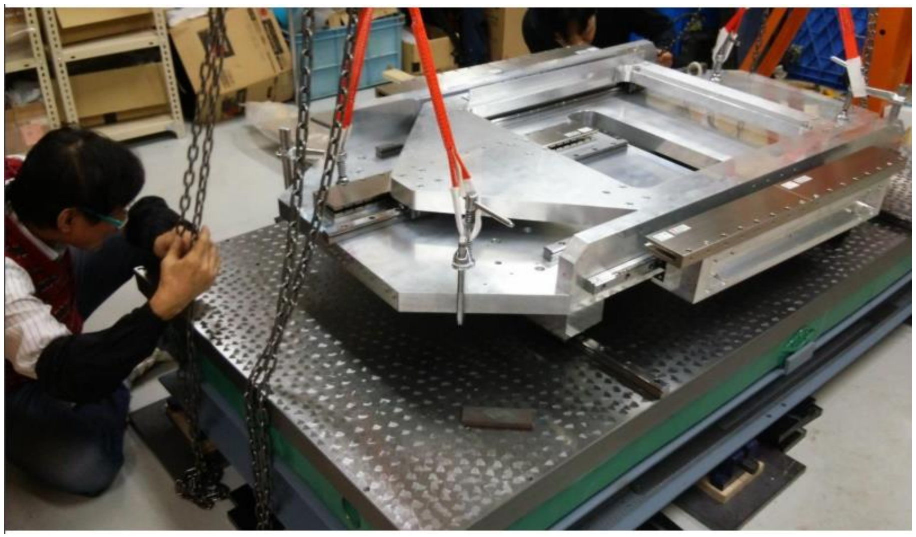
Emulsion film production

- 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



New scanning system under construction at Nagoya University

- HTS II
  - 2.5 m^2/hour, 5 times faster than HTS
  - Will be ready in 2020.



- Large FOV 5x5 mm^2
- Tilted optics FOV
- GPU based processing
- Linear motor and counter weight

- → Readout time necessary for each physics run will be less than 1 year (incl. the detector optimizations)

Summary

- **DsTau studies tau neutrino production** in 400 GeV proton beam dump, for future tau neutrino measurements.

  Collecting 1000 Ds → τ → X double kink events

  from 2.3×10^8 proton tungsten interactions

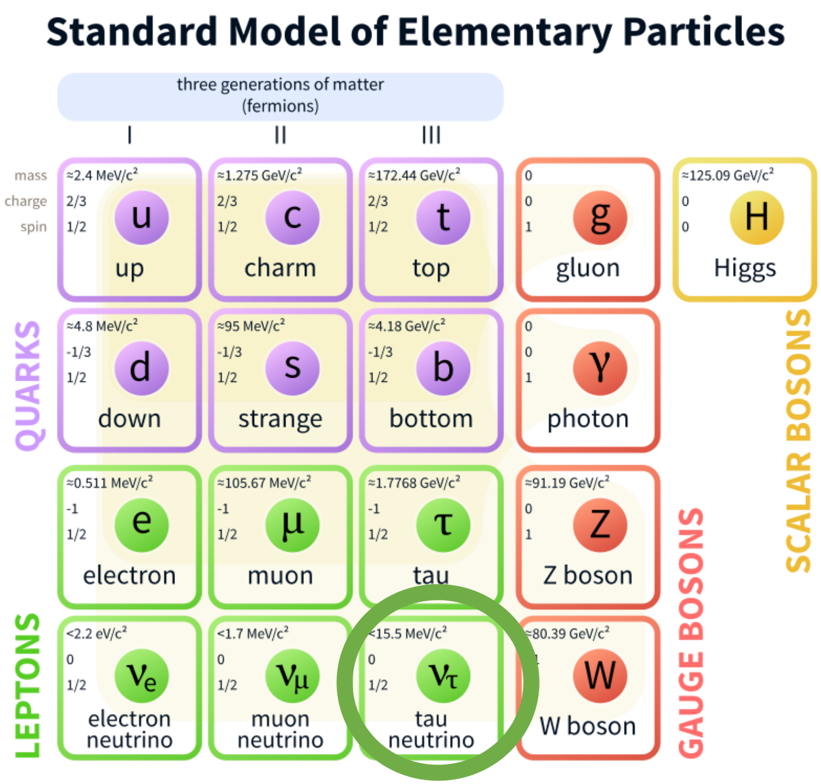
- 2018 was devoted to the pilot run and the establishment of analysis chain.
  - **Pilot run in 2018 was successfully performed** with **1/10 scale** of the total.
  - **57.7% of films were scanned, to be completed in 2019**
  - Data analysis is ongoing (data/MC, double charm)
  - Charm analysis in a statistical way

- A paper summarizing test beams have been submitted.

  arXiv:1906.03487 (submitted to JHEP)

- **Preparing for physics run in 2021/2022 (CERN NA65)**
  - Detector optimization & faster readout to ensure a delivery of timely results

Tau neutrino



3rd generation of lepton

Predicted after discovery of tau in 1975

Consolidated by LEP, $N_\nu = 3$, in 80s

First direct observation in 2001
The last observed fermion

Neutrino oscillations
$\nu_\mu \to \nu_\tau$ appearance in 2015

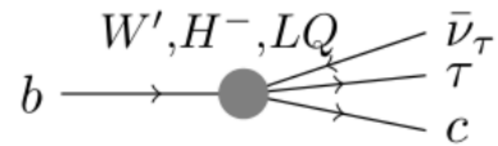
Recently, "Flavor anomalies" in B decays $\bar{B} \to \tau\nu_\tau D^{(*)}$

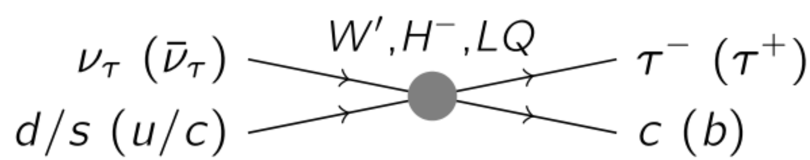
New physics effect?

- There might be additional forces for between leptons and quarks, breaking Lepton Universality
- Several theoretical models.
  - Commonly discussed:
    W’, H^- and LQ
- Intensively discussed in collider environment
- How about neutrino scattering?
  - New particles might affect tau neutrino cross-sections

SM

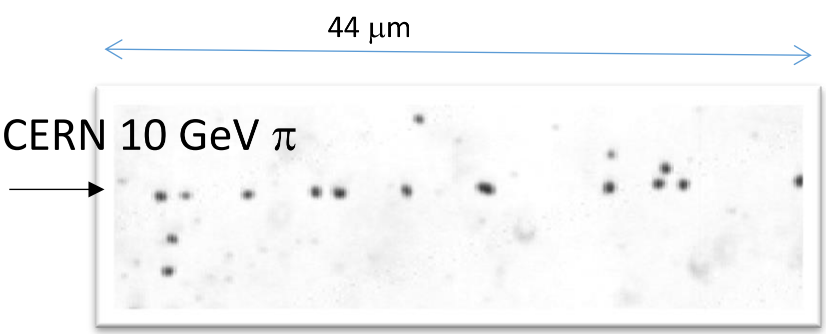
NP

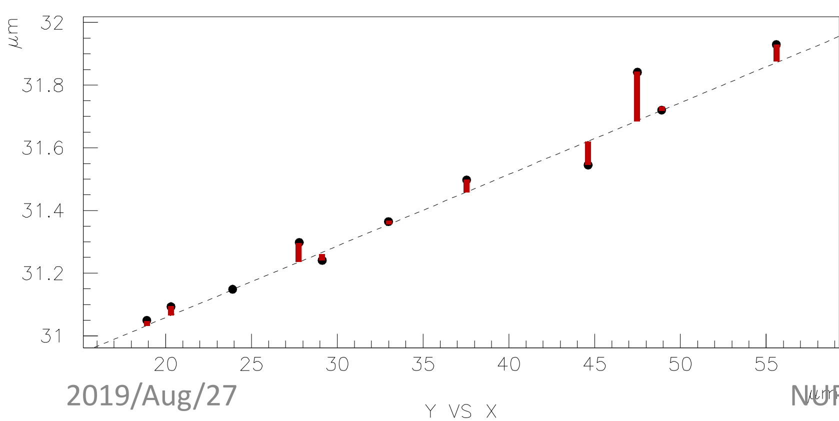


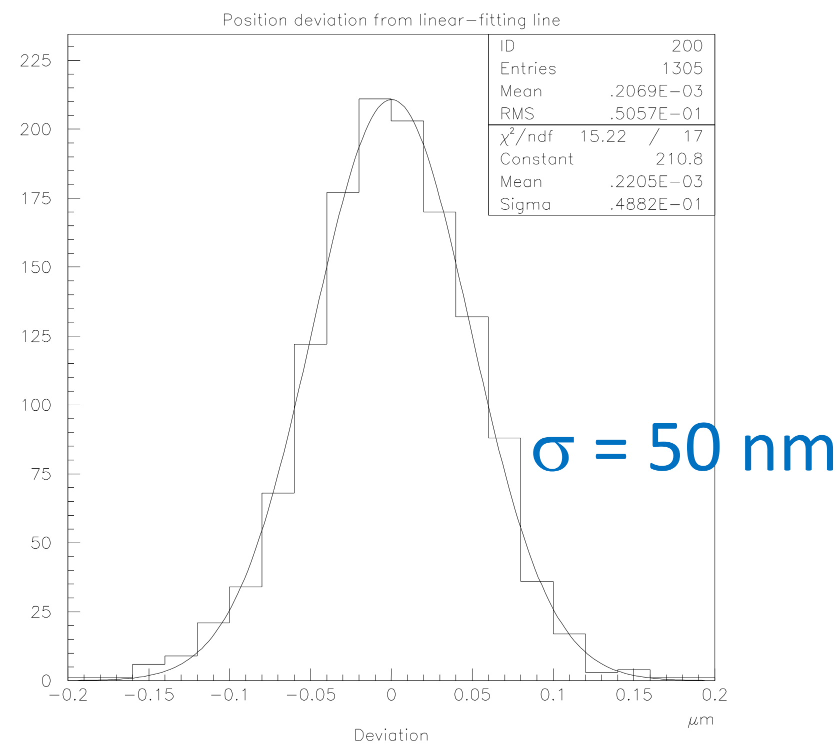


Intrinsic resolution of emulsion detector

- Precision measurement of hits (5nm)
- Deviation of grains from a fit line
- Resolution was found to be 50 nm
  - 0.35 mrad angular resolution

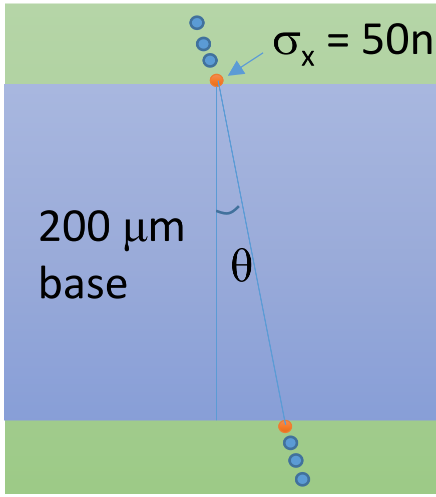


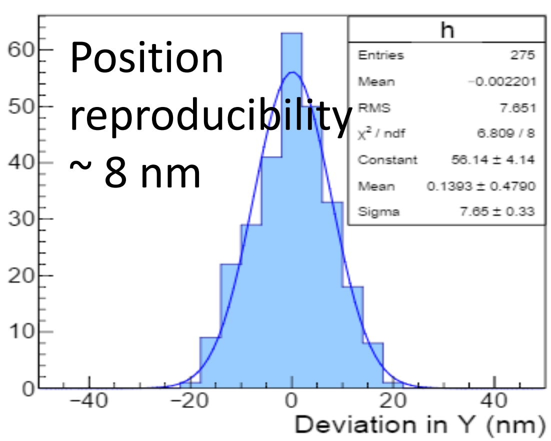


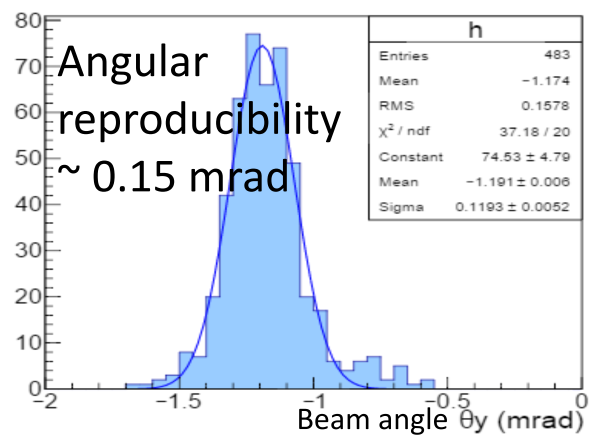


High precision measurement of track angles

- 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



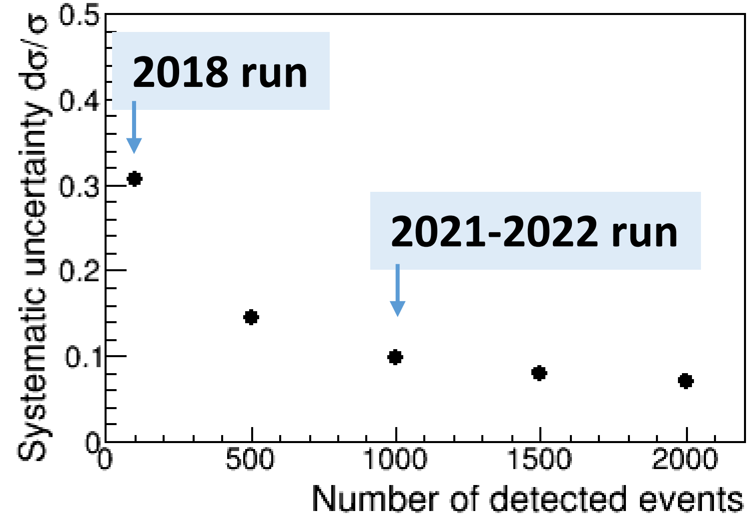




Piezo objective scanner

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 ($D_s \to \tau$)	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

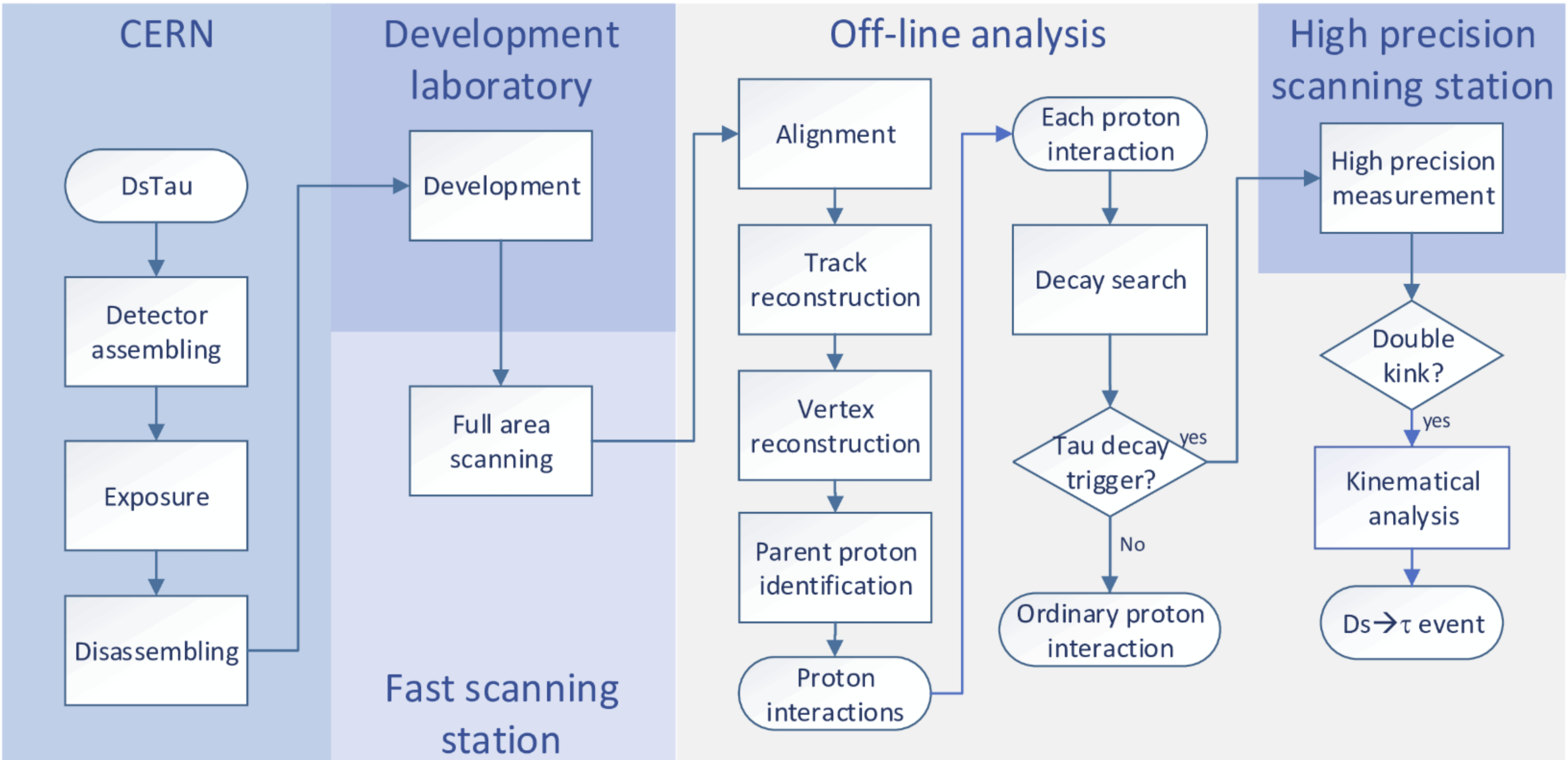
Charm production cross section results

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

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		

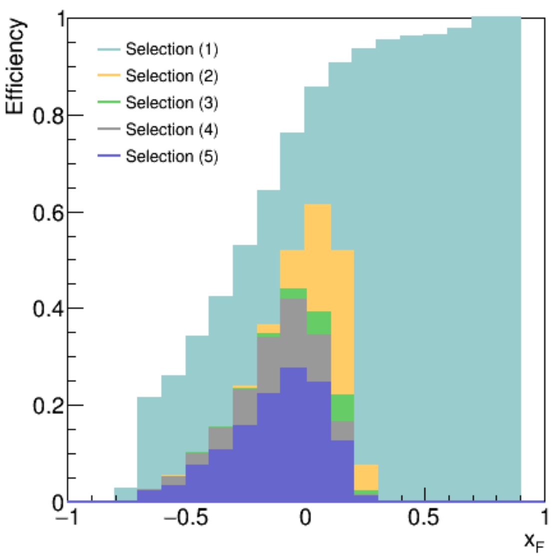
(Results from LHCb at $\sqrt{s}$ = 7, 8 or 13 TeV are not included since the energies differ too much)

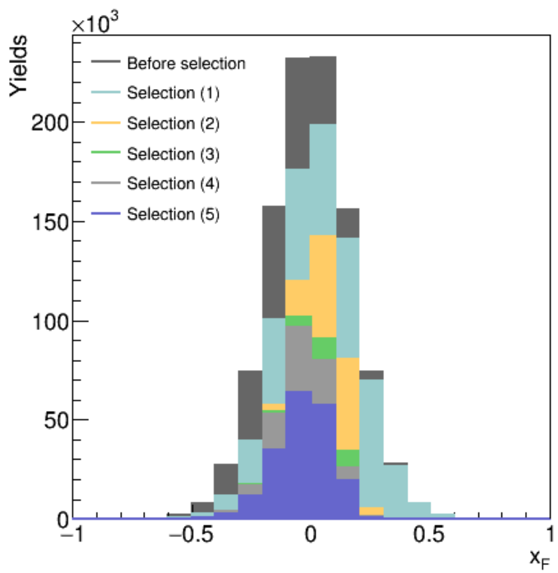
No experimental result effectively constraining the D_s differential cross section at the desired level or consequently the ν_τ production


CERN
Development laboratory
Off-line analysis
High precision scanning station
DsTau
Detector assembling
Exposure
Disassembling
Development
Full area scanning
Fast scanning station
Alignment
Track reconstruction
Vertex reconstruction
Parent proton identification
Proton interactions
Each proton interaction
Decay search
Tau decay trigger?
yes
No
Ordinary proton interaction
High precision measurement
Double kink?
yes
Kinematical analysis
Ds→τ event

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

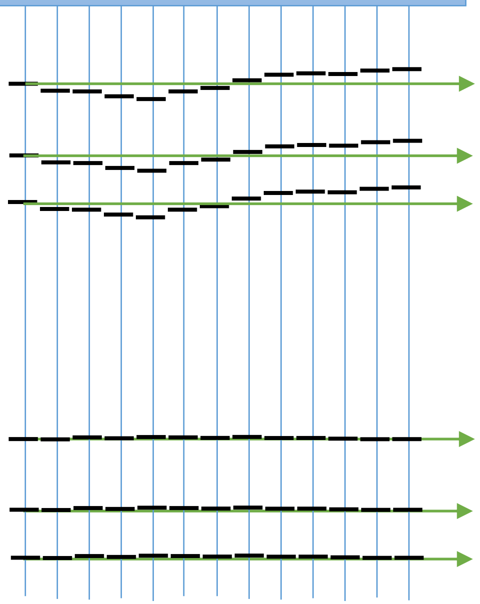




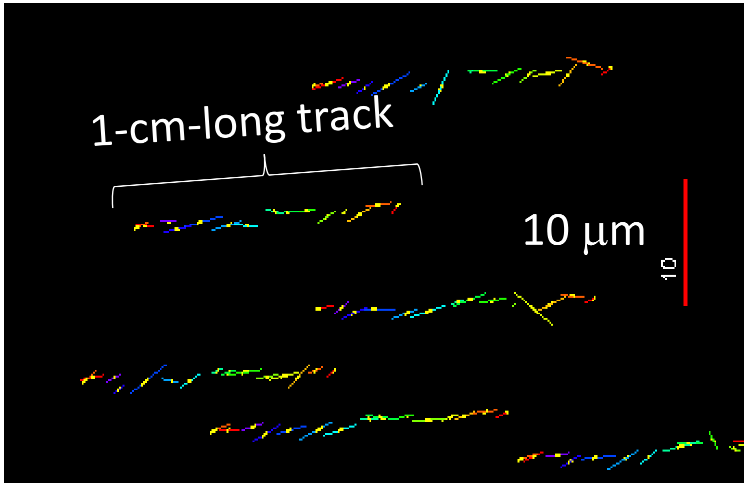
Alignment of between emulsion films

- "**Proton tracks run straight!**"
    - scattering of 400 GeV proton is negligible
- Align films to minimize the displacement from the beam proton
- Position residual of track segments to a linear fit is < 0.4 μm, depending on processing area size

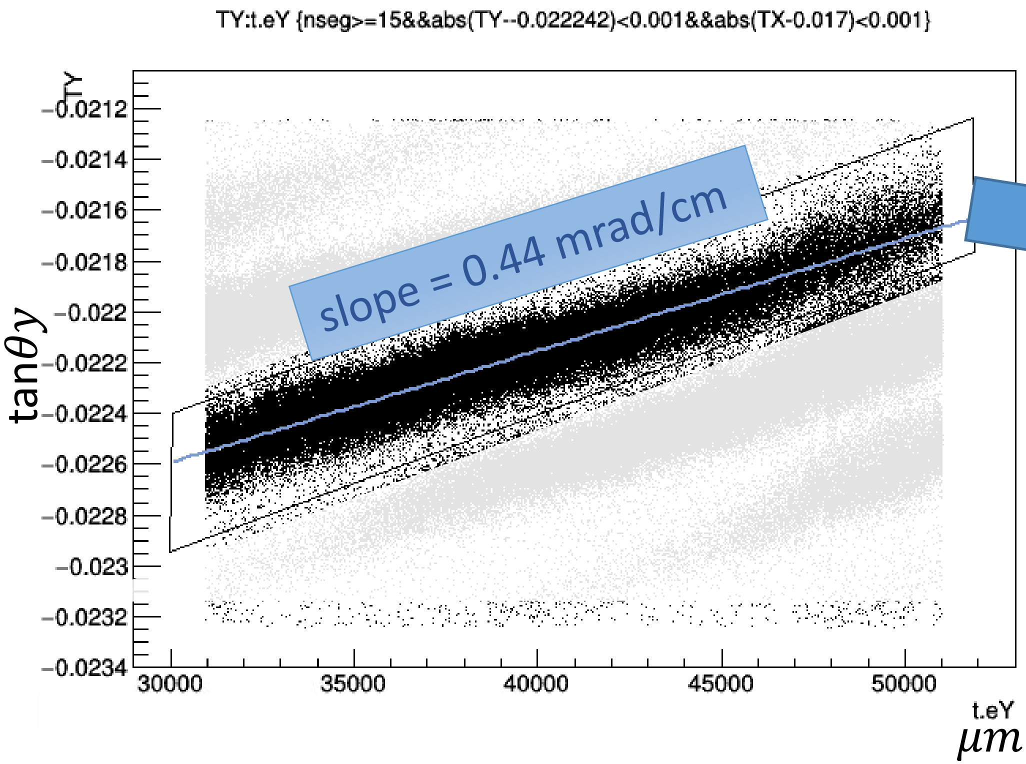
Align films with proton tracks



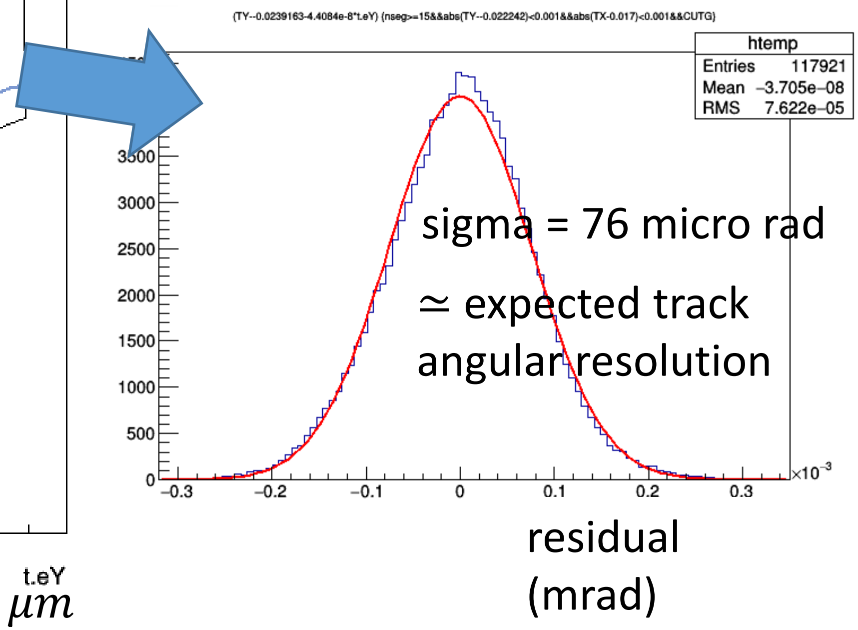
Correct segment position



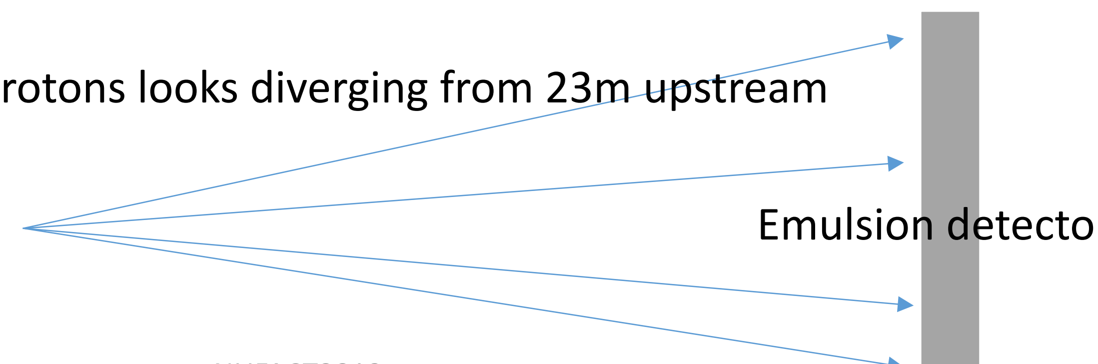
Close look in the TY



- Residual from the fit.



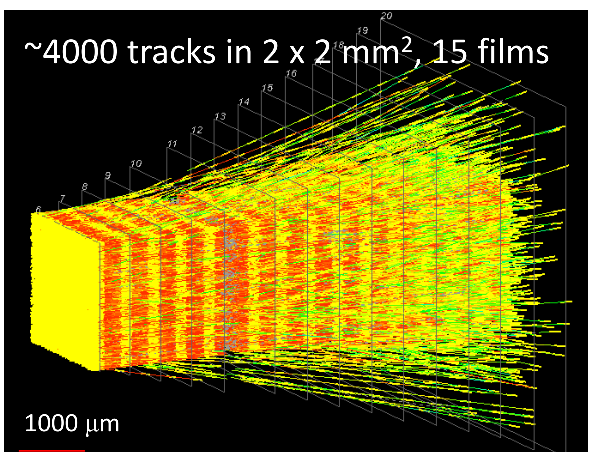
The "right-shoulder up" feature is consistent with a "diverging beam".
1/(0.44mrad/cm) = 23m.



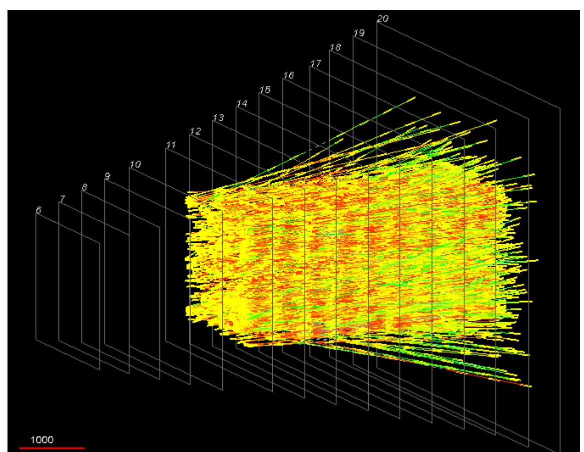
Reconstruction of proton interactions

- 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 will be processed in the 2018 pilot run (50 m^2)
  - 10 GB / film after compression to be stored
- 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)

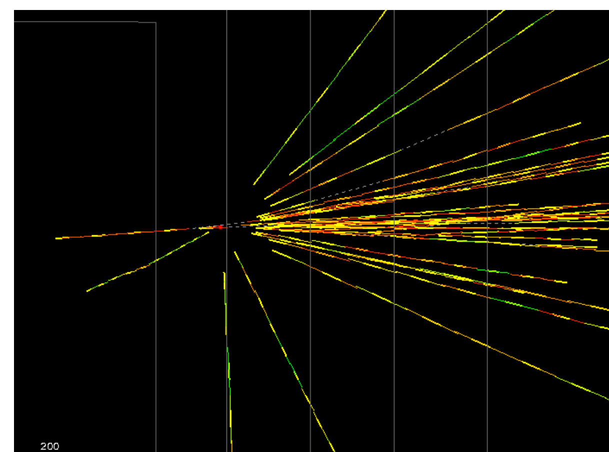
Reconstructed tracks



Tracks starting after tungsten



Vertex reconstruction



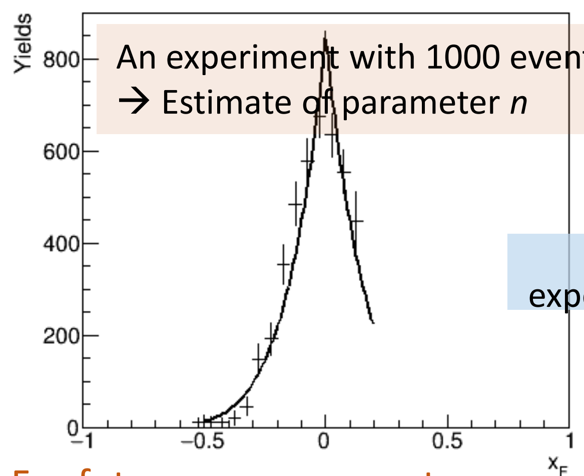
Estimation of parameter *n* for DONUT re-evaluation

Ds differential cross section

Parametrization used in DONUT

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

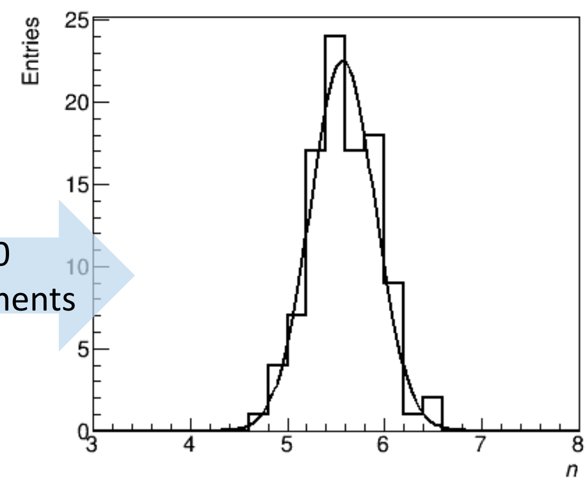
Reconstructed x_F
(corrected by the efficiency)



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)

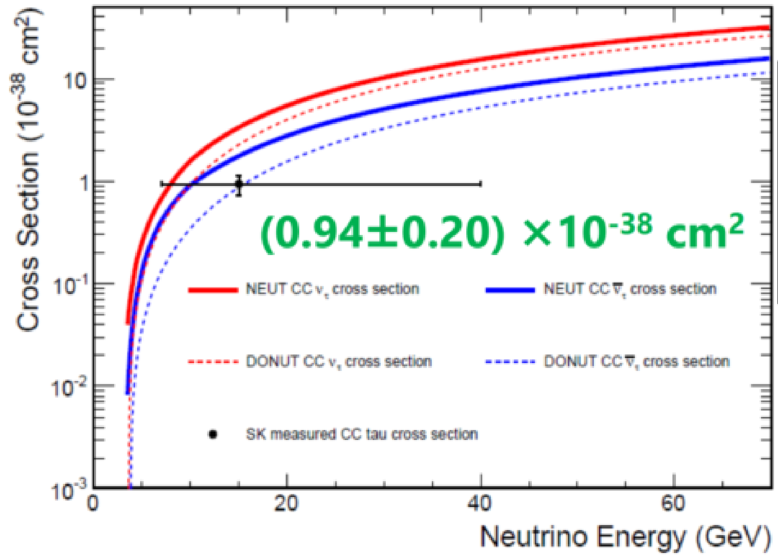
ν_τ cross section measurement by oscillated neutrinos

SK

Atmospheric

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

σ_{meas}=(1.47±0.32) σ_{theory}



arXiv:1711.09436

Presented 1st day by Guillaume Pronost

OPERA

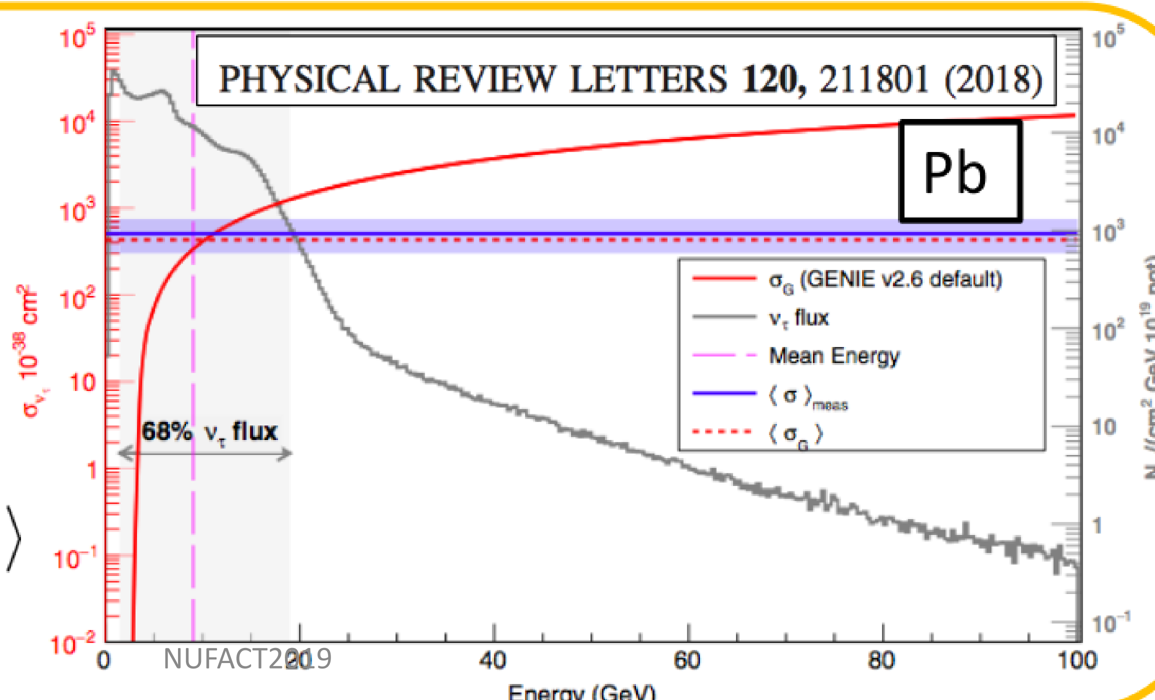
CNGS ν_μ beam

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

σ with a Pb nucleus

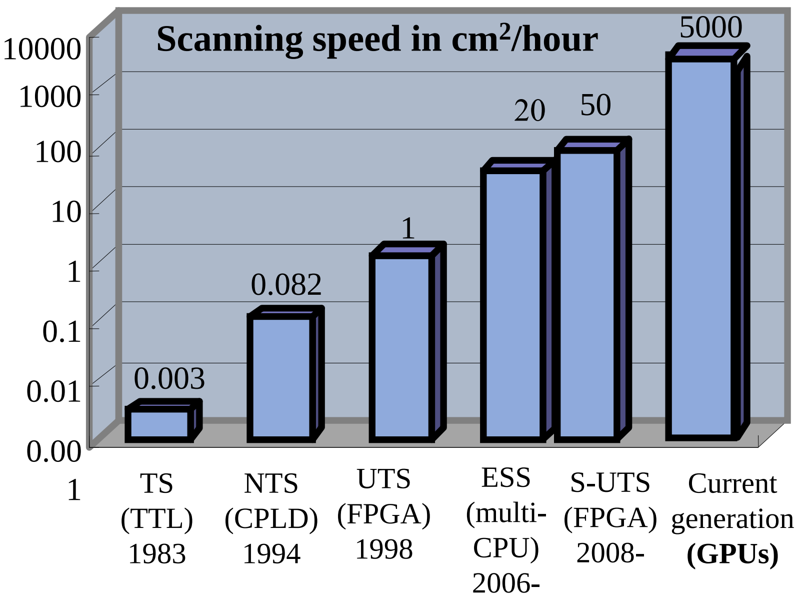
$\langle\sigma\rangle_{\rm meas} = (5.1^{+2.4}_{-2.0}) \times 10^{-36}\ {\rm cm}^2$,

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



Evolution of automated scanning system

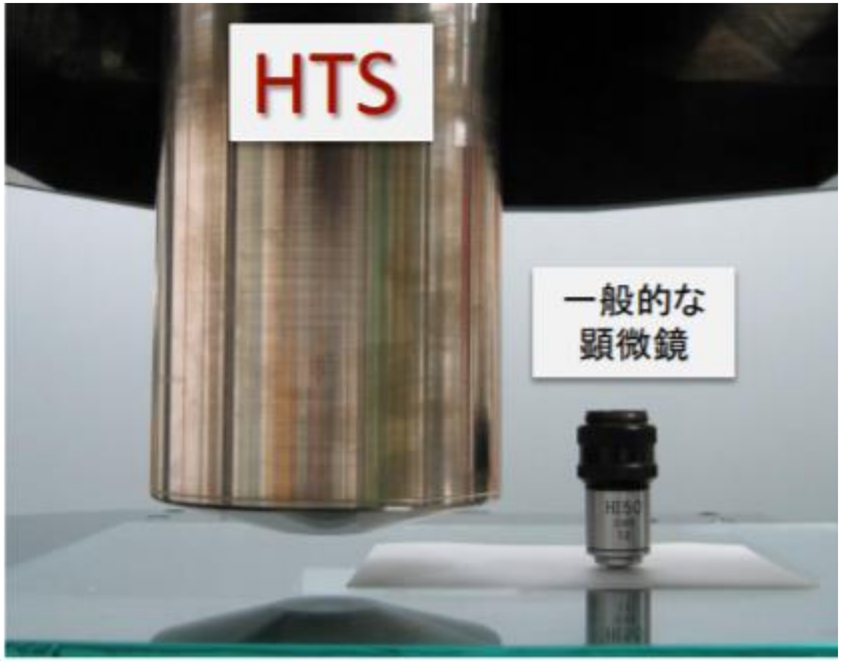
Development of scanning system started in 1970s.



100 times faster than OPERA

HTS concept

- Very large field of view
  5 x 5 mm^2 (x600 cf. SUTS)
- Quick stage using the linear motors (good transfer characteristic) and counter stage.
- GPGPU based image processing
  <100ms @tanθ<1.6 (Geforece GTX680)



	FOV	Frequency	Scan speed
SUTS	0.04mm^2	50Hz	72cm^2/h
HTS (running)	25mm^2	5Hz	4500cm^2/h
HTS / SUTS	x600	x1/10	x62
HTS2 (under dev.)	50mm^2	15Hz equiv.	25000cm^2/h

Continuous image capturing

- Length of view 5mm vs Emulsion 60μm → 12mrad=0.7°
- Image segmented into 18 per length of a side (5mm)
- Capture 18 frames per 5mm stage (emulsion) travel