Tau-neutrino production study in 400 GeV proton interactions

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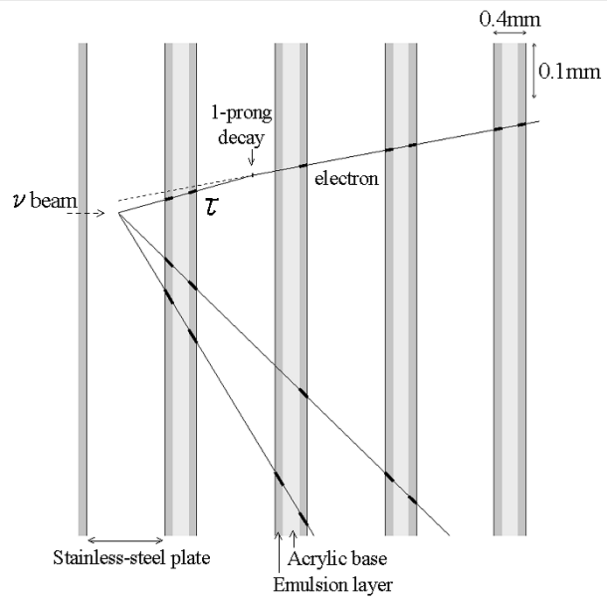
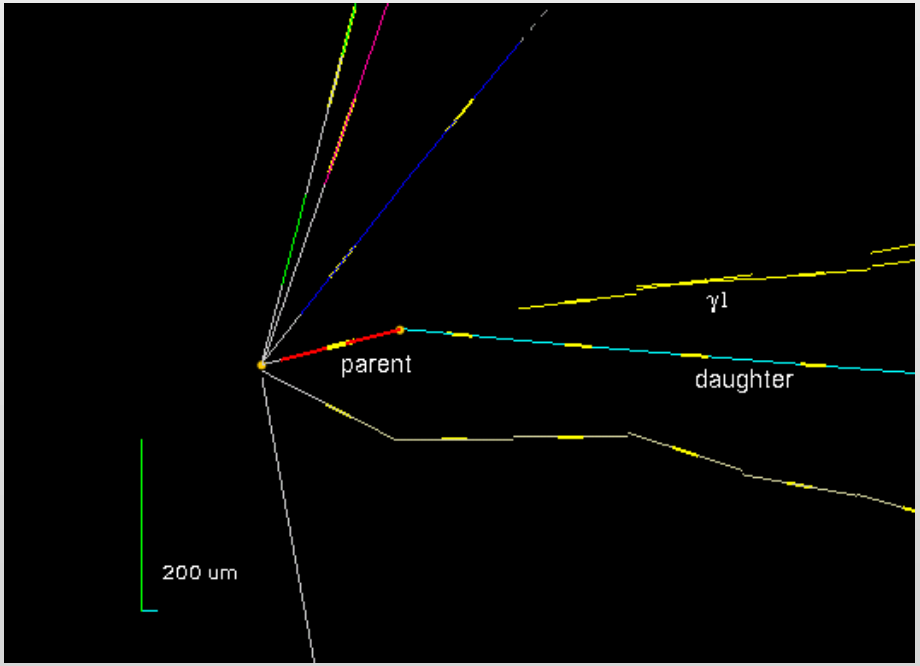
On behalf of the DsTau Collaboration

Physics motivation

- Tau-neutrino: less studied particle in the standard model
  - DONuT: First direct observation of ν_τ interactions (9 ν_τ candidate events observed)
  - OPERA: Discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode (5 ν_τ candidate events)





- Precise measurement of ν_τ CC cross section would be a test of lepton universality in neutrino CC interactions

Status of neutrino CC cross section measurements

ν_μ : measured by many experiments

Average over 30 - 200 GeV

$$\sigma_{\nu\mu}^{const} = (0.51 \pm 0.01) \times 10^{-38} cm^2 GeV^{-1}$$

~2% error

ν_τ : only the DONuT experiment

ν_τ source is D_S produced in proton interactions:

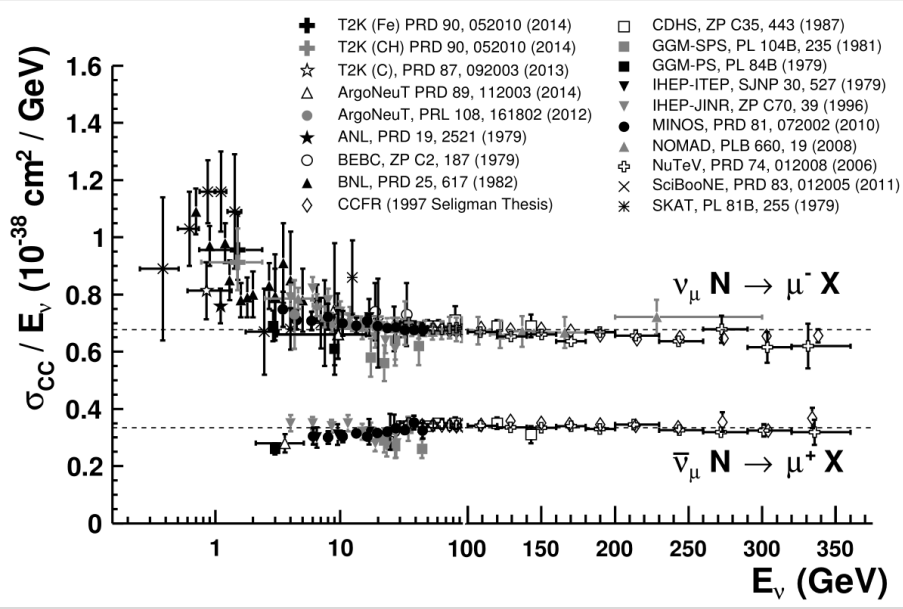
$D_s^+ \rightarrow \tau^+ \nu_\tau \rightarrow X \bar{\nu}_\tau \nu_\tau$

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

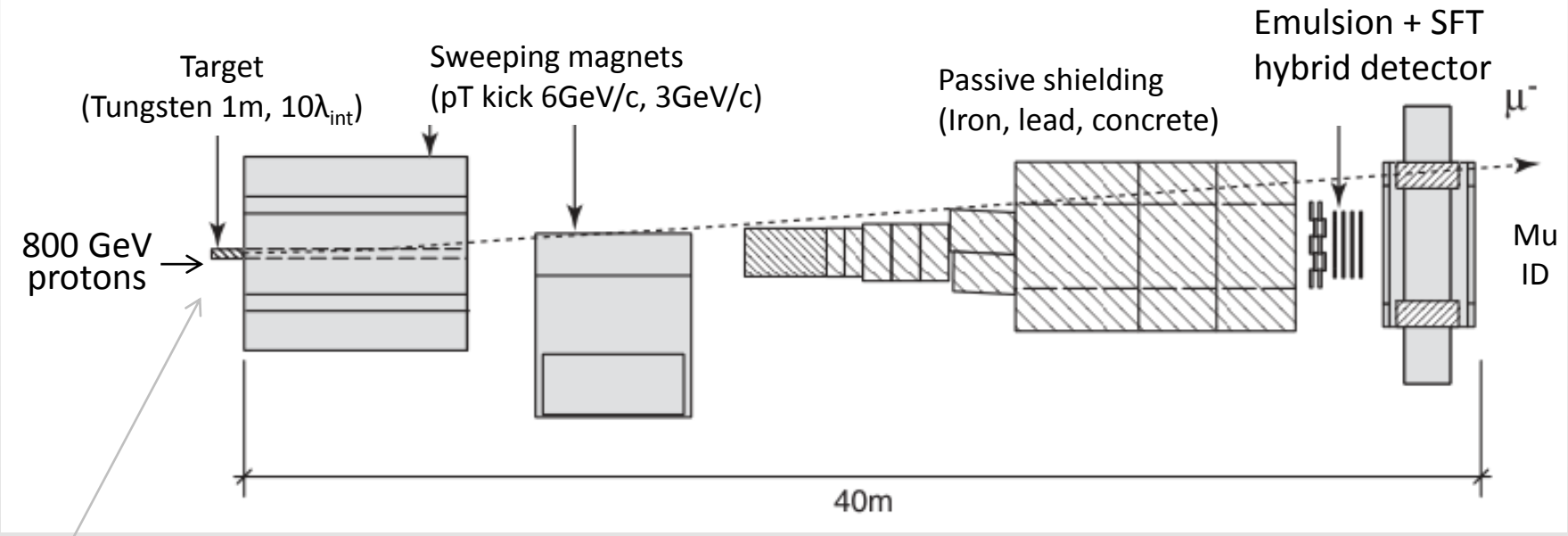
No experimental data on the D_s differential production cross section ($d\sigma/dx_F$) in high energy proton interaction

>50% systematic uncertainty in the cross section measurement

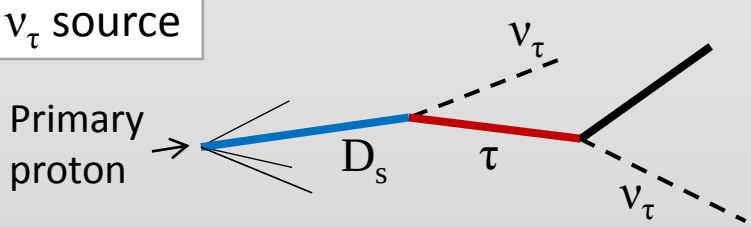
Muon neutrino CC inclusive cross sections (PDG 2014 and 2015 update)



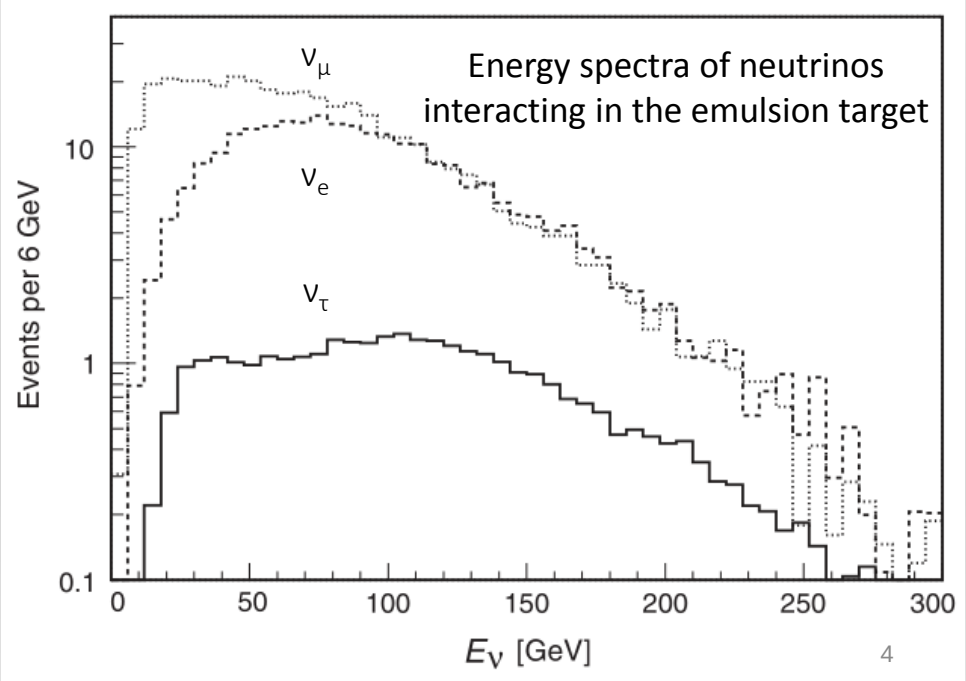
Neutrino beam line in DONuT (Fermilab E872)



ν_τ source



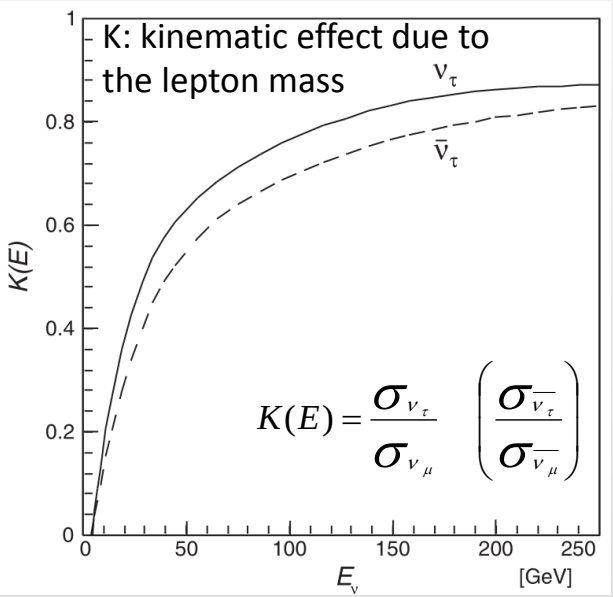
	Main source
ν_e	D^0 , $D^\pm$, D_s , Λ_c
ν_μ	D^0 , $D^\pm$, D_s , Λ_c , π, K
ν_τ	D_s



Cross section measurement in DONuT

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

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



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

Phenomenological formula used to describe charmed particles

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

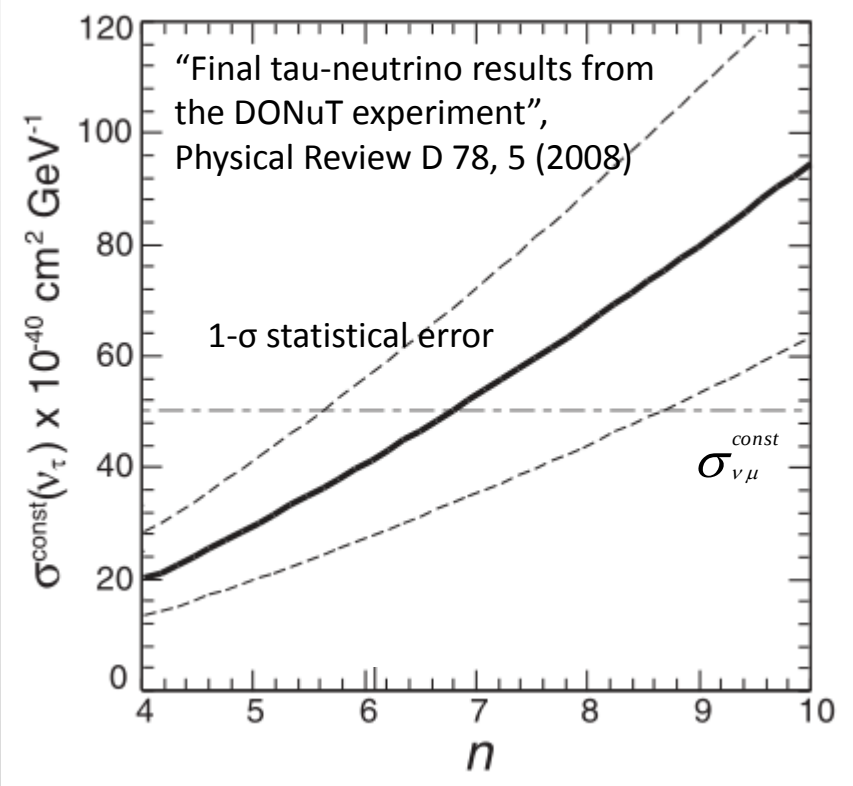
x_F is Feynman x ($x_F = 2p^{CM}_z/\sqrt{s}$) and p_T is transverse momentum

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

The energy-independent part was parameterized as

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

Parameter-dependent cross section result by DONuT



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

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

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

By measuring the longitudinal part of D_s production, we can re-evaluate the cross section

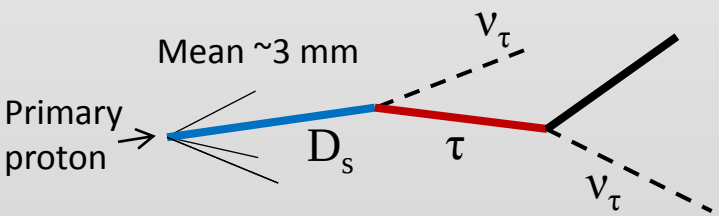
New experiment

The DsTau project: Tau-neutrino production study at the CERN SPS

- **Aim**: Improve knowledge of tau-neutrino production
  - Re-evaluate existing ν_τ cross section (DONUT result): systematic uncertainty >50% → ~10%
  - Provide essential data for future ν_τ experiments, e.g. SHiP
- **Method**: Direct measurement of tau-neutrino production in 400 GeV proton interactions
  - Dominant source (>95%): $D_s \rightarrow \tau\, \nu_\tau \rightarrow X\, \nu_\tau\, \nu_\tau$
  - Detect the double-kink topology within a few mm by emulsion detector
  - Measure x_F distribution (D_s momentum estimation using topological variables)
- **Status**
  - LoI submitted to the CERN-SPSC in Feb 2016 → positive feedback
  - Prototype test experiment in Nov. 2016

Proton target:
tungsten foil + emulsion tracker

Double-kink topology



Small kink of $D_s \rightarrow \tau$
Mean 7 mrad

The collaboration

Japan:
Aichi
Kobe
Nagoya

Romania:
Bucharest

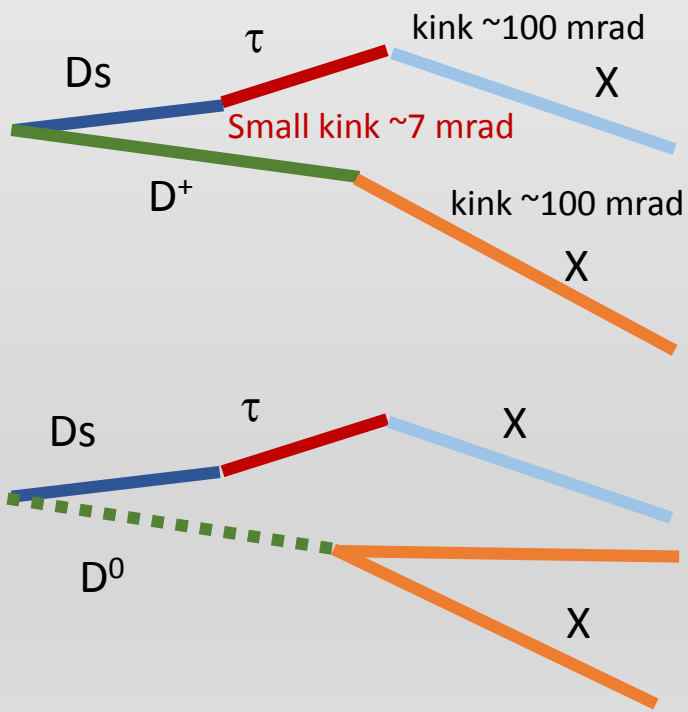
Russia:
Dubna

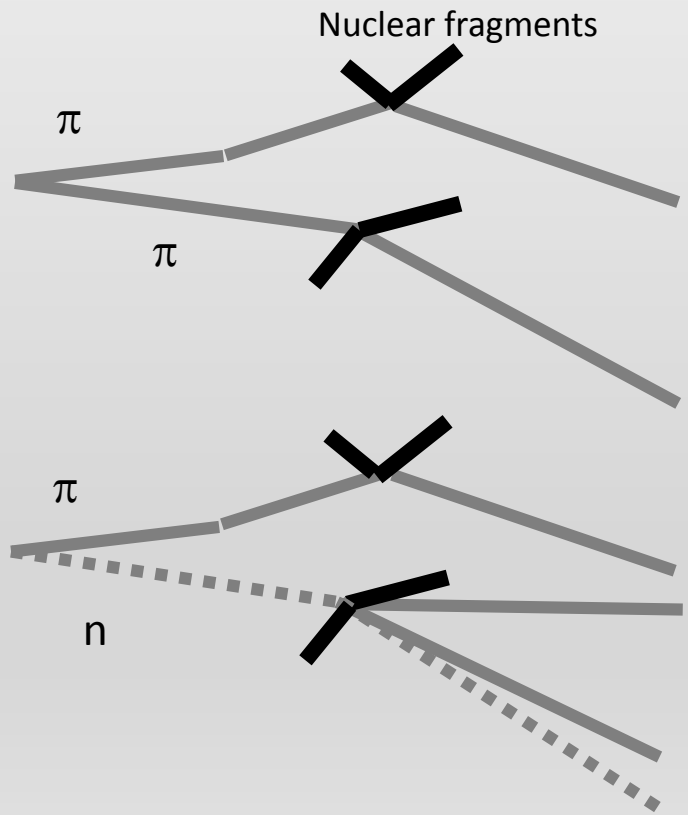
Switzerland:
Bern

Turkey:
Ankara

Signal and background

- Signal: a double kink + a charmed particle decay
- Main background: hadron interactions

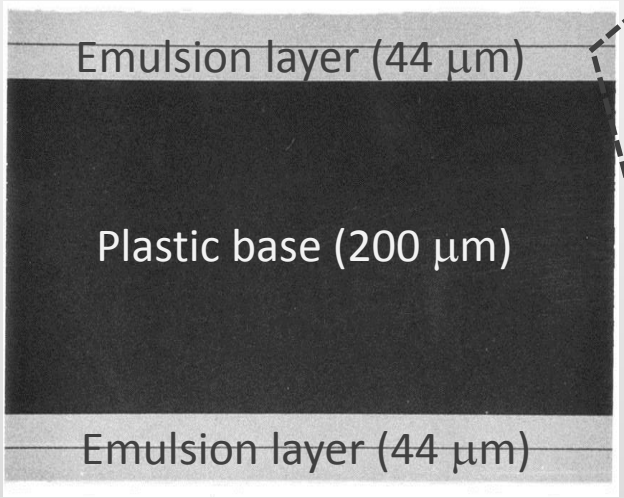




Emulsion detectors: highest position resolution

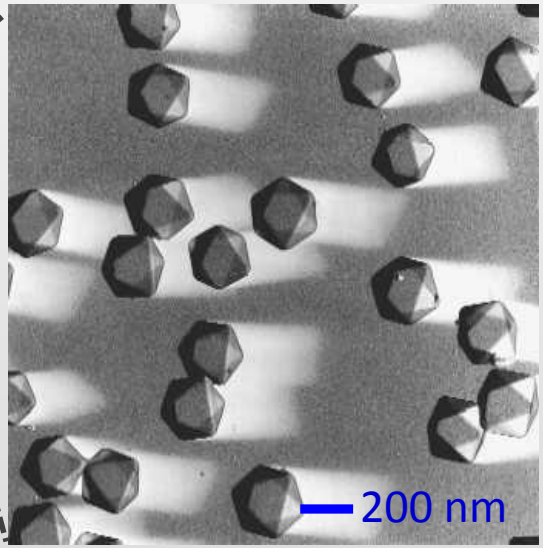
Emulsion film

Cross-sectional view

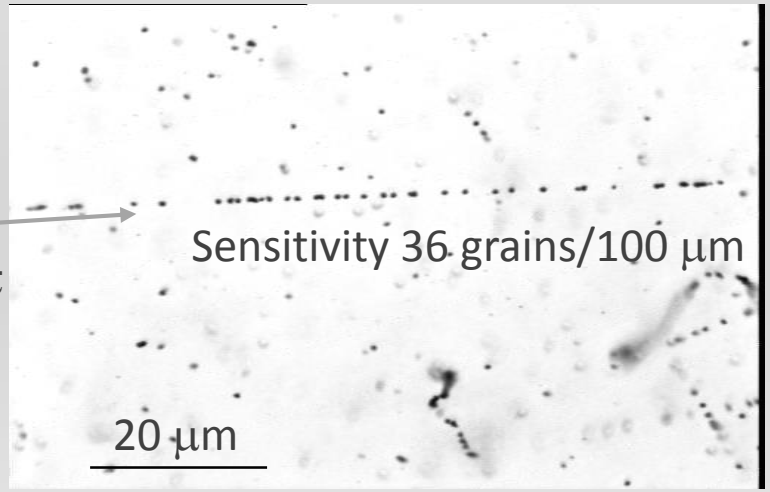


AgBr crystal

10^{14} crystals in a film



10GeV/c π beam



3D tracking device
Intrinsic resolution 50 nm

Emulsion research facility in Bern

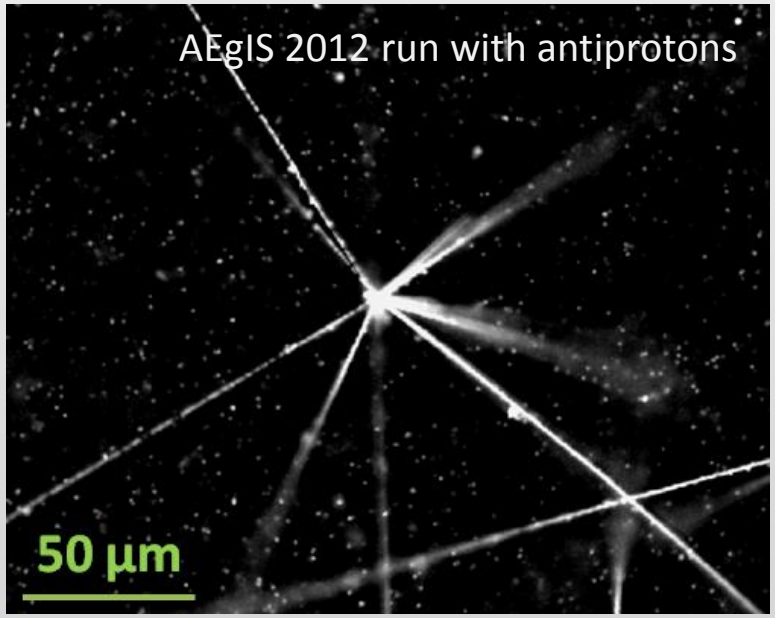
Detector production and R&D

Automated emulsion scanning microscopes

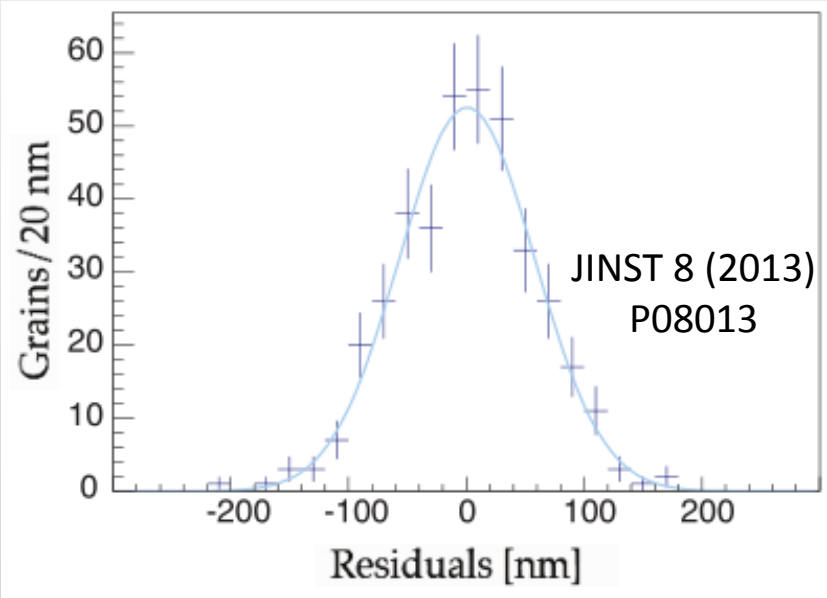
- Dedicated emulsion facility
  - 30 m deep underground lab
  - Detector production chain and photographic development chain
  - Dedicated R&D program for several kinds of special emulsions, collaborating with Nagoya University in Japan
- High speed readout system
  - Fast 4π track recognition based on GPU technology (A. Ariga and T. Ariga, Journal of Instrumentation 9 P04002 (2014))
  - Upgrade ongoing

Intrinsic resolution of emulsion detectors

Emulsion detector produced in Bern using high sensitivity emulsion gel produced in Nagoya University



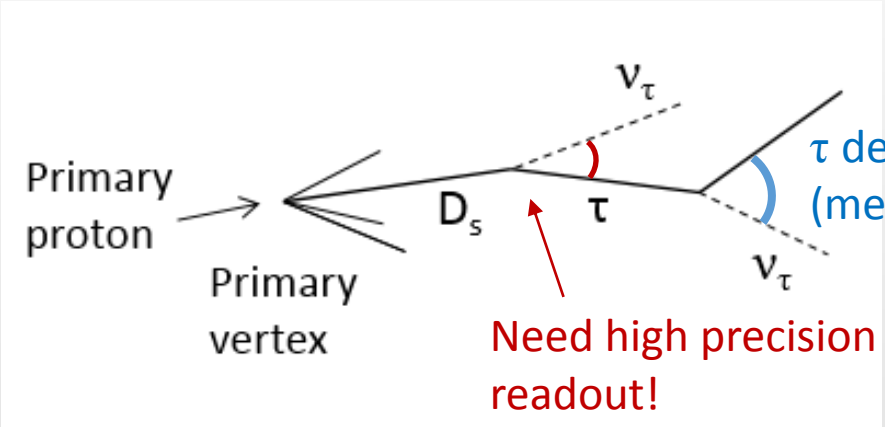
Measured intrinsic resolution



Intrinsic resolution 58 nm →

Angular resolution 0.05µm·√2/200µm = **0.35 mrad**

Detection of $D_s \rightarrow \tau \rightarrow X$ events (double-kink topology)

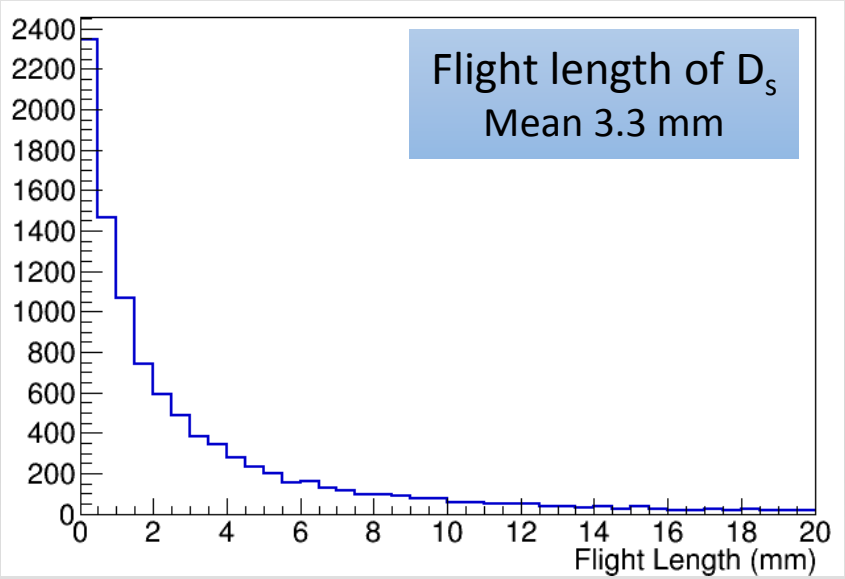


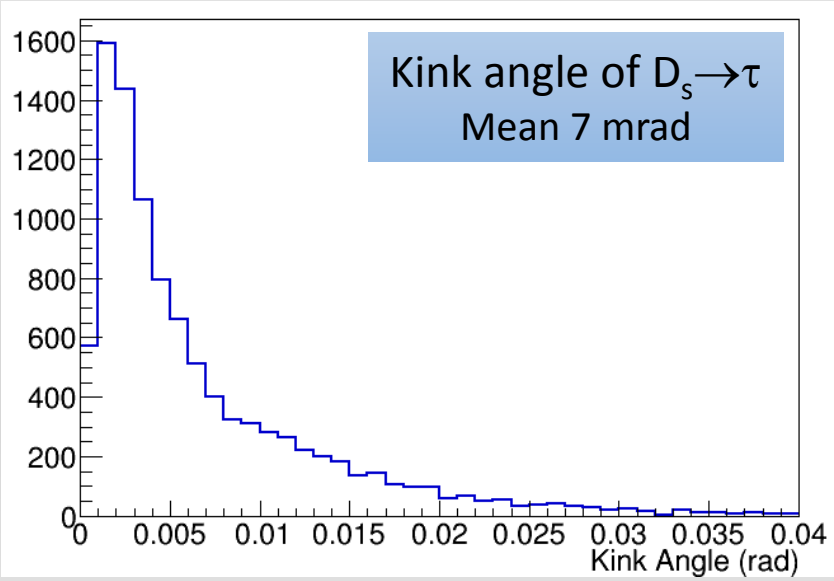
τ decay can be easily detected by standard readout (mean kink angle ~100 mrad)

The analysis chain:

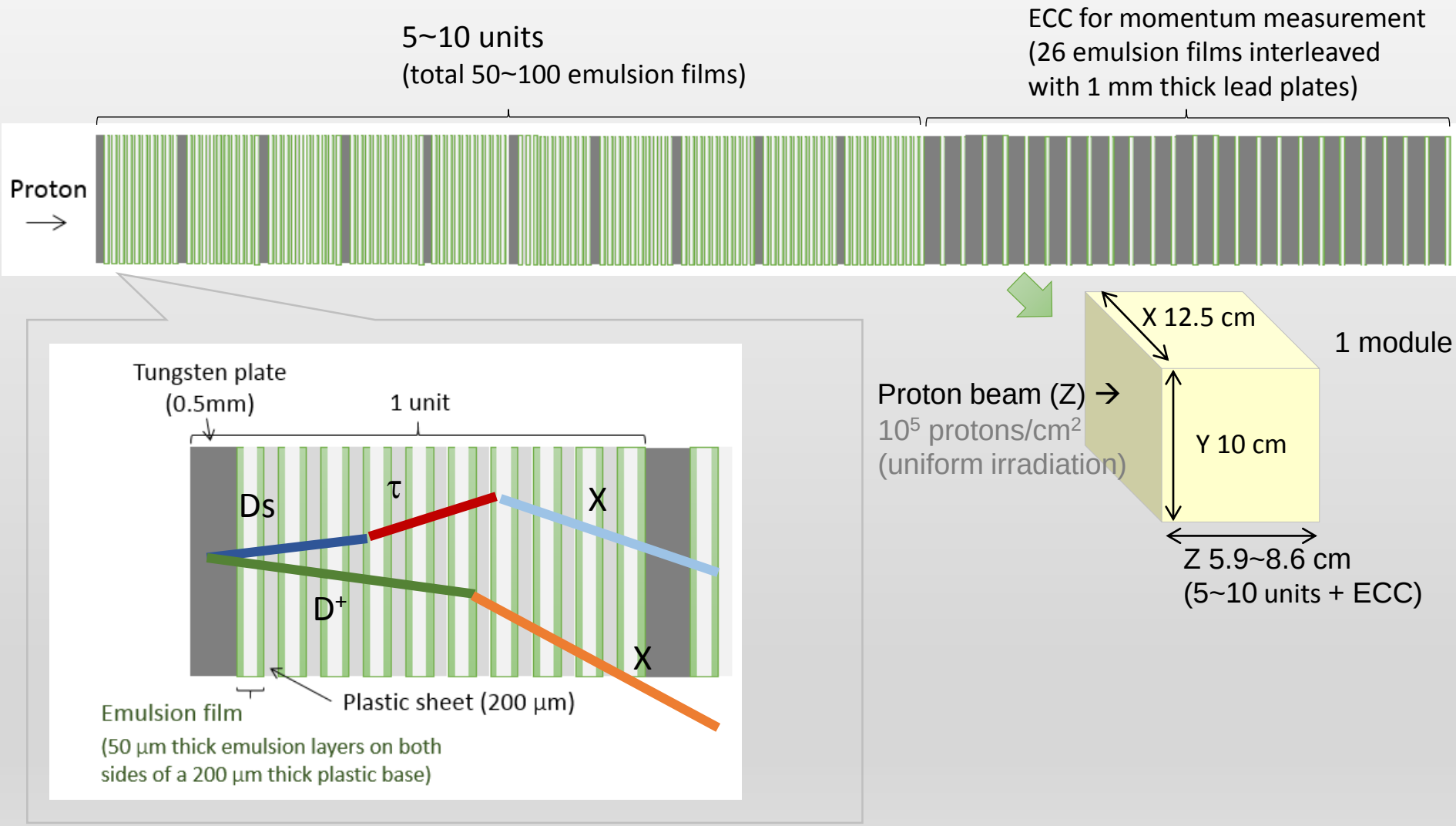
1) Tag $\tau \rightarrow X$ decay

2) Perform high precision measurement to detect $D_s \rightarrow \tau$ decay

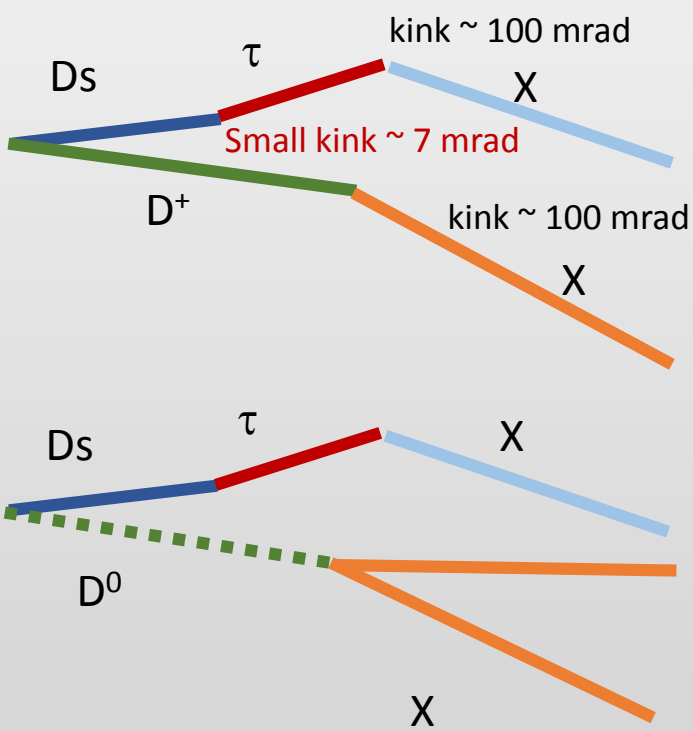




Module structure for $D_s \rightarrow \tau \rightarrow X$ measurement



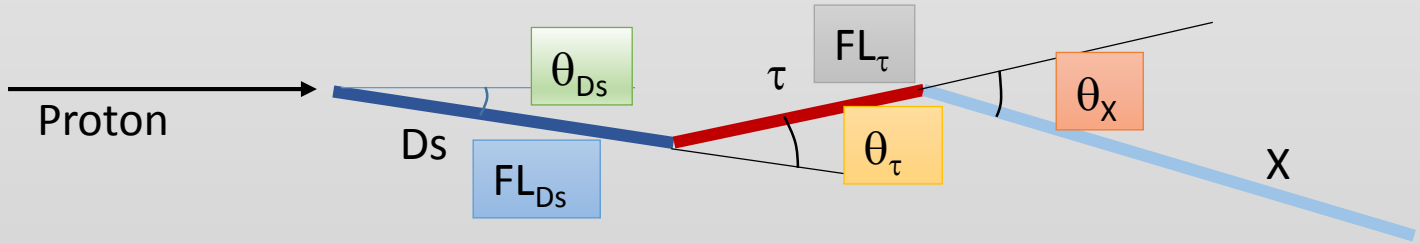
Signal efficiency



Selection (FL: Flight Length, Δθ: kink angle)	**Total efficiency**	
	D_s^+	**D_s^-**
$FL(D_s)$> 2 emulsion layers	78%	77%
($FL(\tau)$> 2 layers & $\Delta\theta(D_s \rightarrow \tau)$> 2mrad) or ($FL(\tau)$> 1 layer & $\Delta\theta(D_s \rightarrow \tau)$> 15mrad)	44%	43%
$FL(D_s)$<5mm & $FL(\tau)$<5mm	32%	31%
$\Delta\theta(\tau)$>15mrad	30%	28%
Pair charm: 0.1mm<FL<5mm & Δθ>15mrad	20%	20%

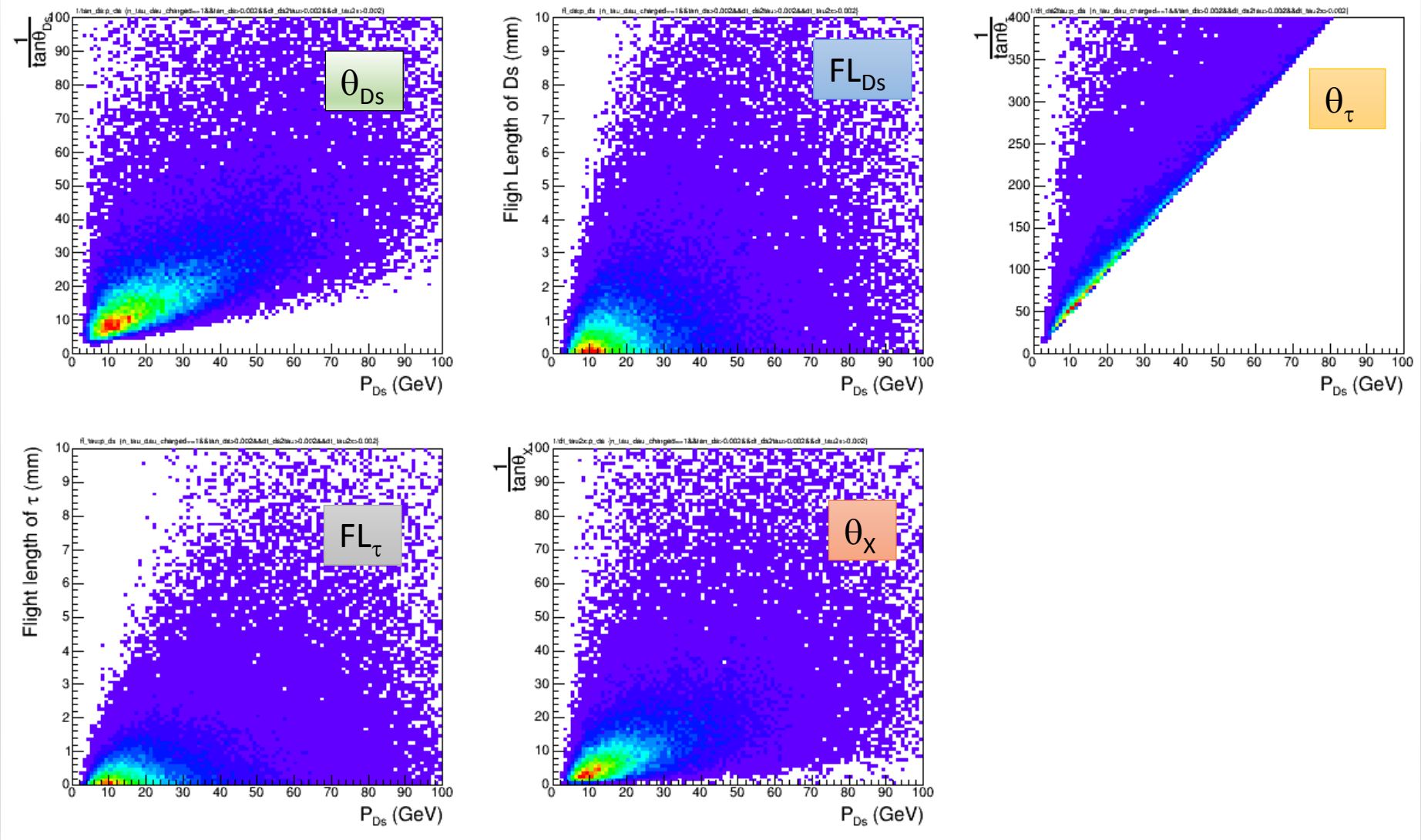
For x_F measurement:
D_s momentum reconstruction from topological variables

- x_F is a longitudinal profile of Ds: $x_F = 2p_z^{CM}/\sqrt{s} = 2\gamma(p_{Ds}^{Lab}\cos\theta_{Ds} - \beta E_{Ds}^{Lab})/\sqrt{s}$
- Ds decays quickly, unable to measure P directly
- Need a method to estimate P_{Ds} from topological variables

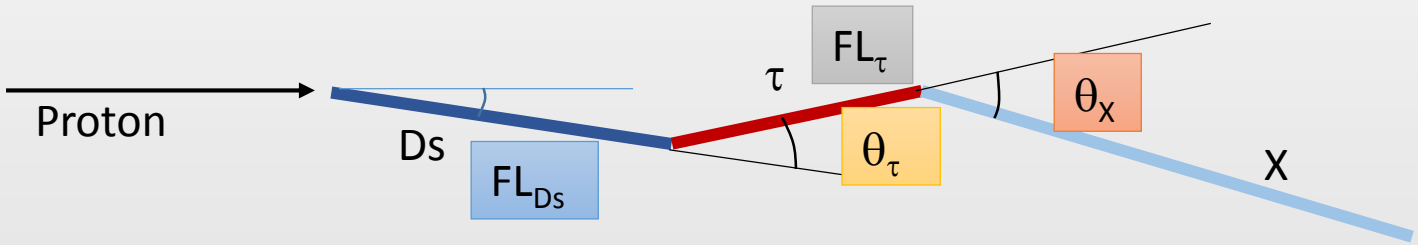


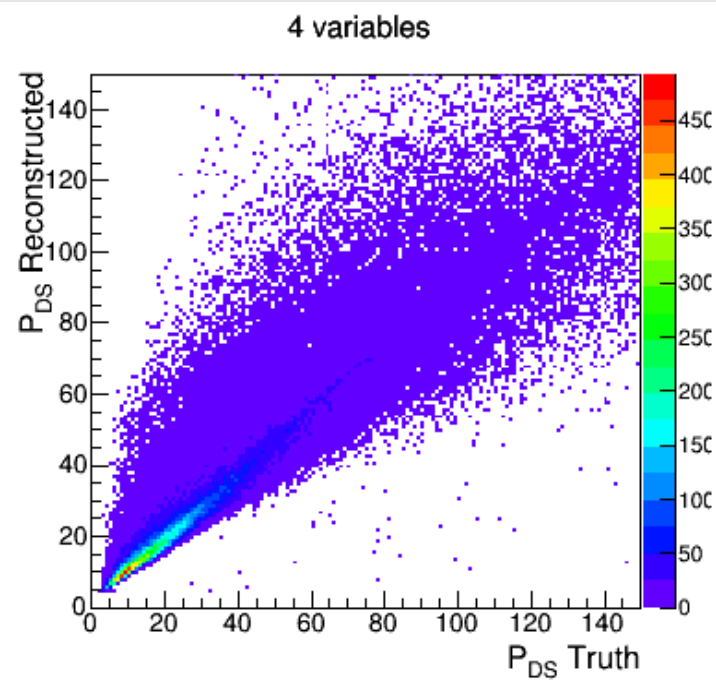
Topological variables: correlation with P_{Ds}

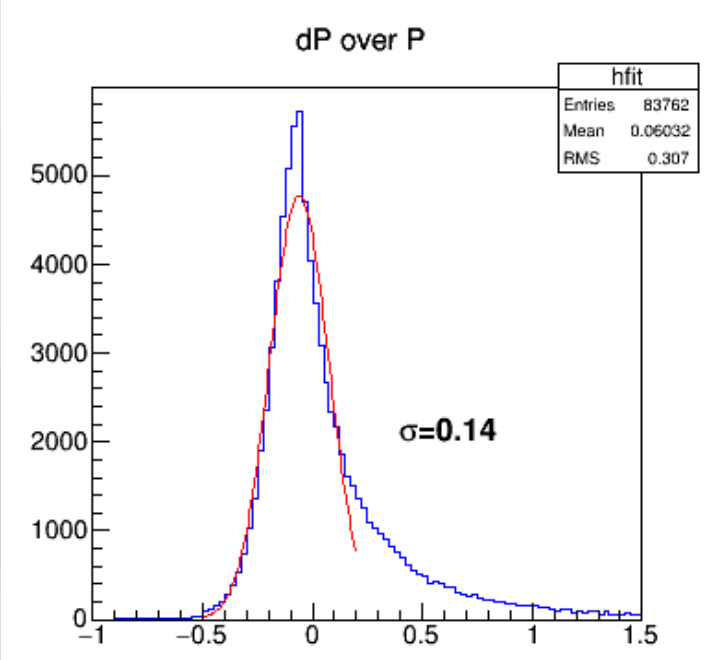
Sample: tau single prong decay



Ds momentum reconstruction by Artificial Neural Network (ANN) using 4 variables





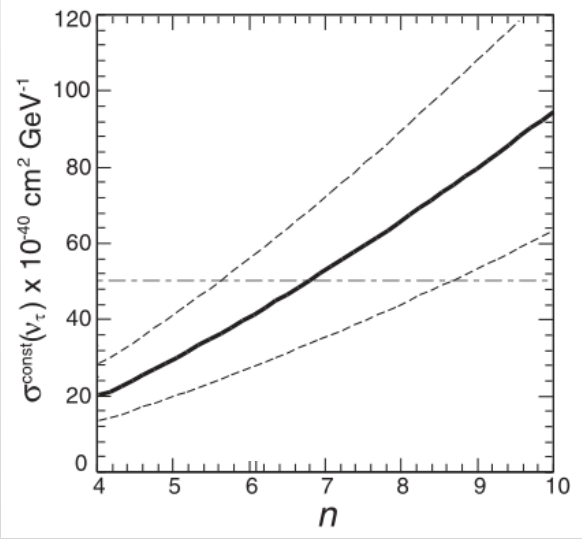


Expected precision for the cross section measurement

Systematic uncertainties

	DONuT	With DsTau
D_s differential cross section (x_F dependence)	~0.50!?	~0.10
Charm production cross section	0.17	~0.03
Decay branching ratio	0.23	
Target atomic mass effects (A dependence)	0.14	

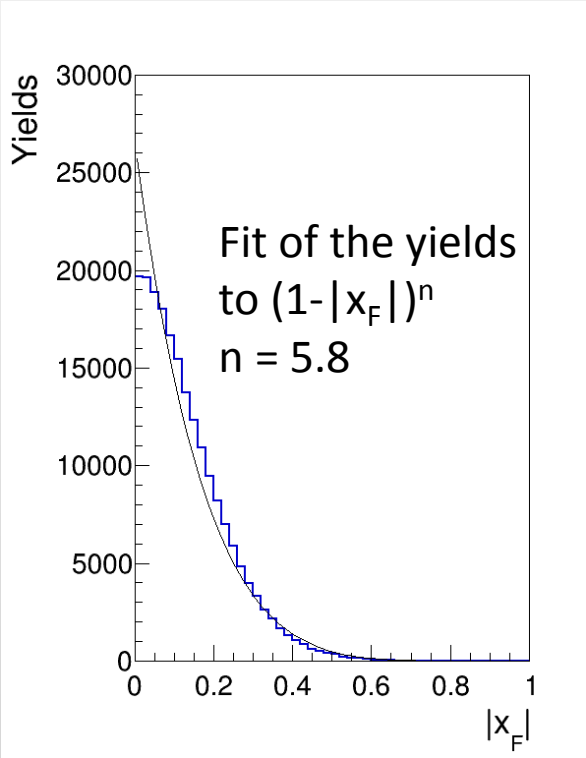
ν_τ CC cross section measured by DONUT as a function of the parameter n



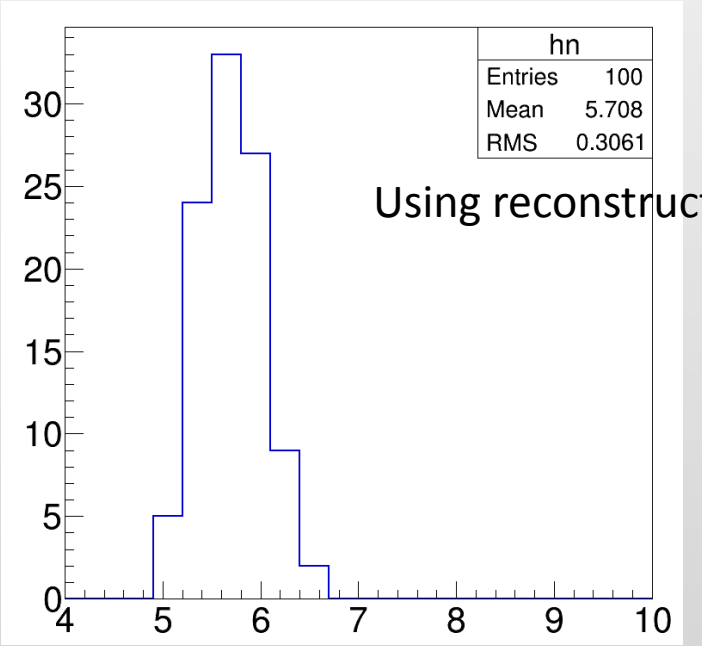
To reach ~10% precision on the cross section,
the parameter n is to be measured with a precision of ~0.3

Expected precision for the measurement of x_F distribution

x_F distribution (100000 events)



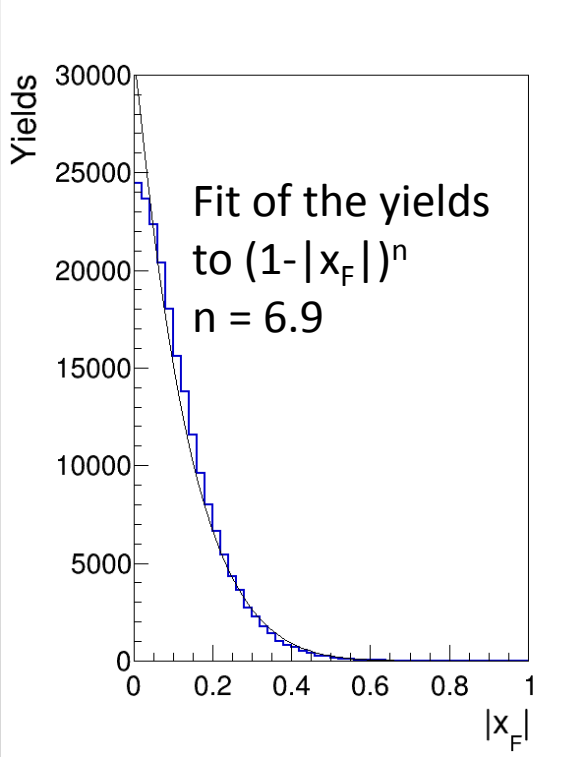
x_F distribution (1000 events) → parameter n
Repeat 100 experiments



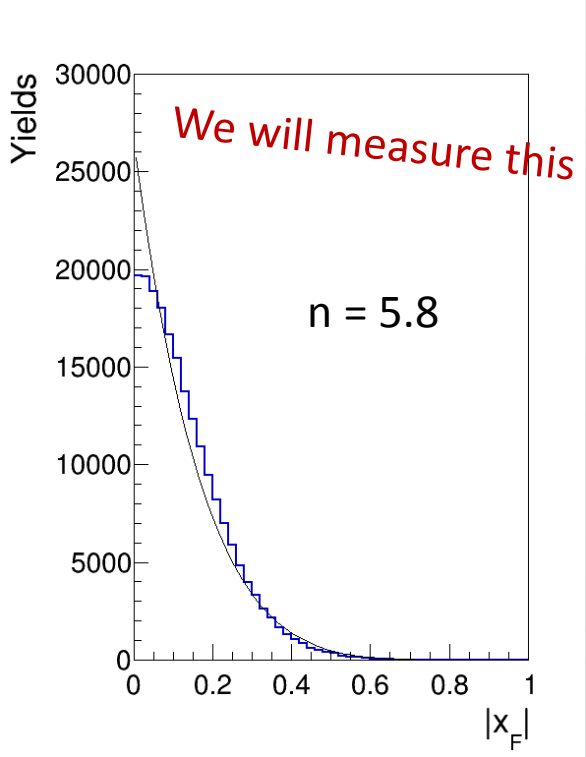
Precision of ~0.3 could be achieved with 1000 events

x_F distributions of $Ds^{\pm}$: energy dependence

800 GeV beam



400 GeV beam



We will measure this distribution

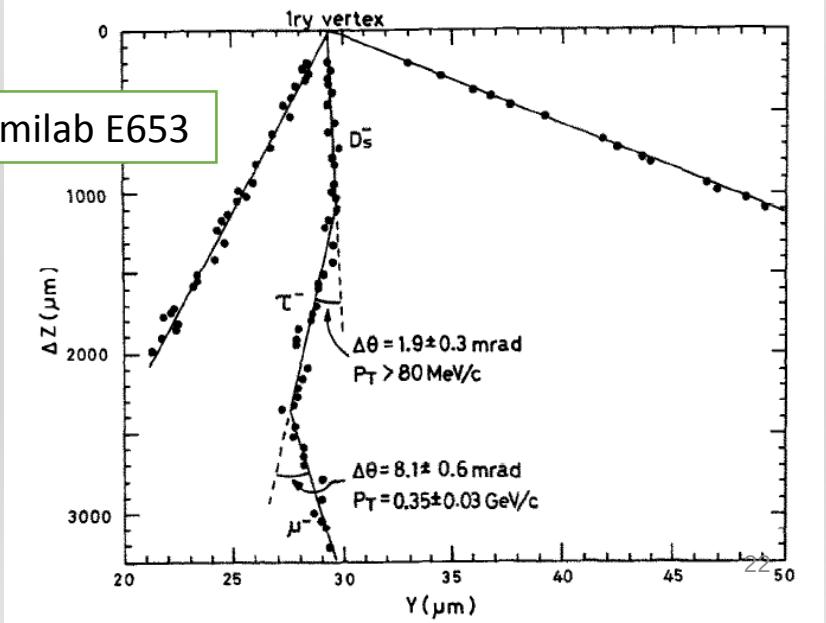
To re-evaluate DONUT result, need to extrapolate 400 GeV data to 800 GeV
The uncertainty is to be estimated

How many interactions to be analyzed?

- To detect 1000 $D_s \rightarrow \tau \rightarrow X$ events
  - Efficiency ~20%, BR($D_s \rightarrow \tau$) = 5.55%
  - 8.2×10^4 D_s to be produced
- D_s production cross section in Tungsten target
  - ~4×10^{-4} @400GeV
- → 2×10^8 proton interactions to be analyzed!

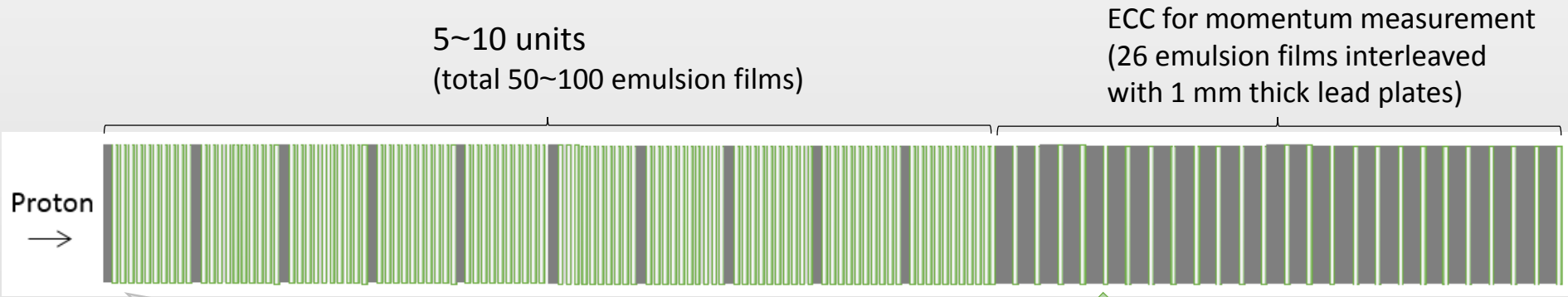
↔ only 10^5 proton interactions were analyzed in emulsions in E653 (previous emulsion hybrid experiment using high energy hadron beams)

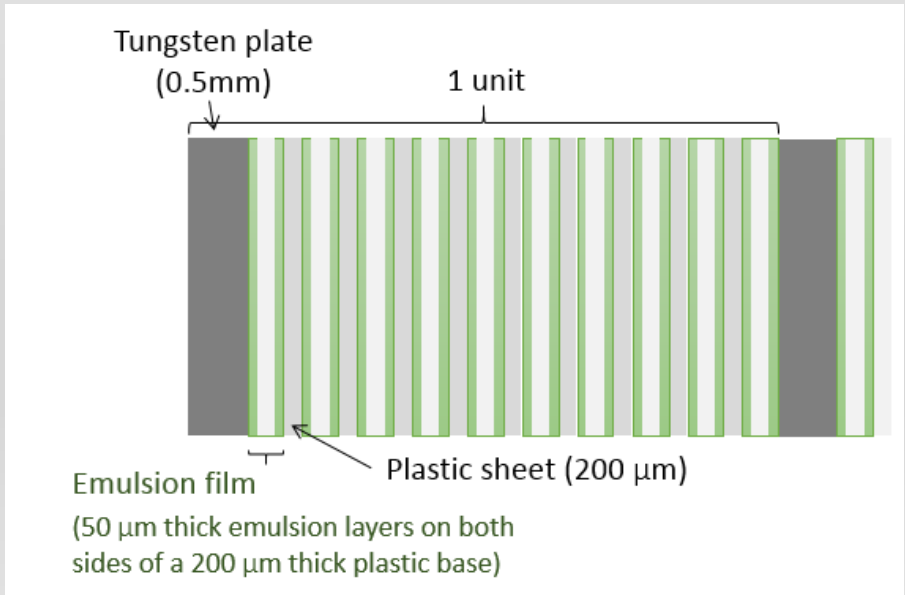
$D_s \rightarrow \tau \rightarrow \mu$ candidate found in Fermilab E653

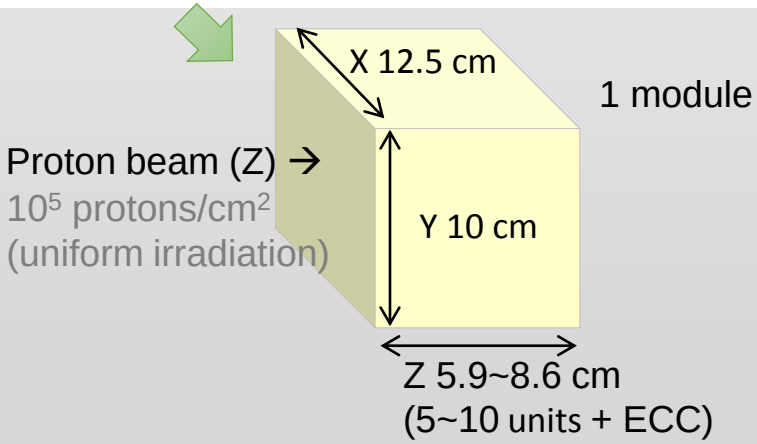


Target and detector

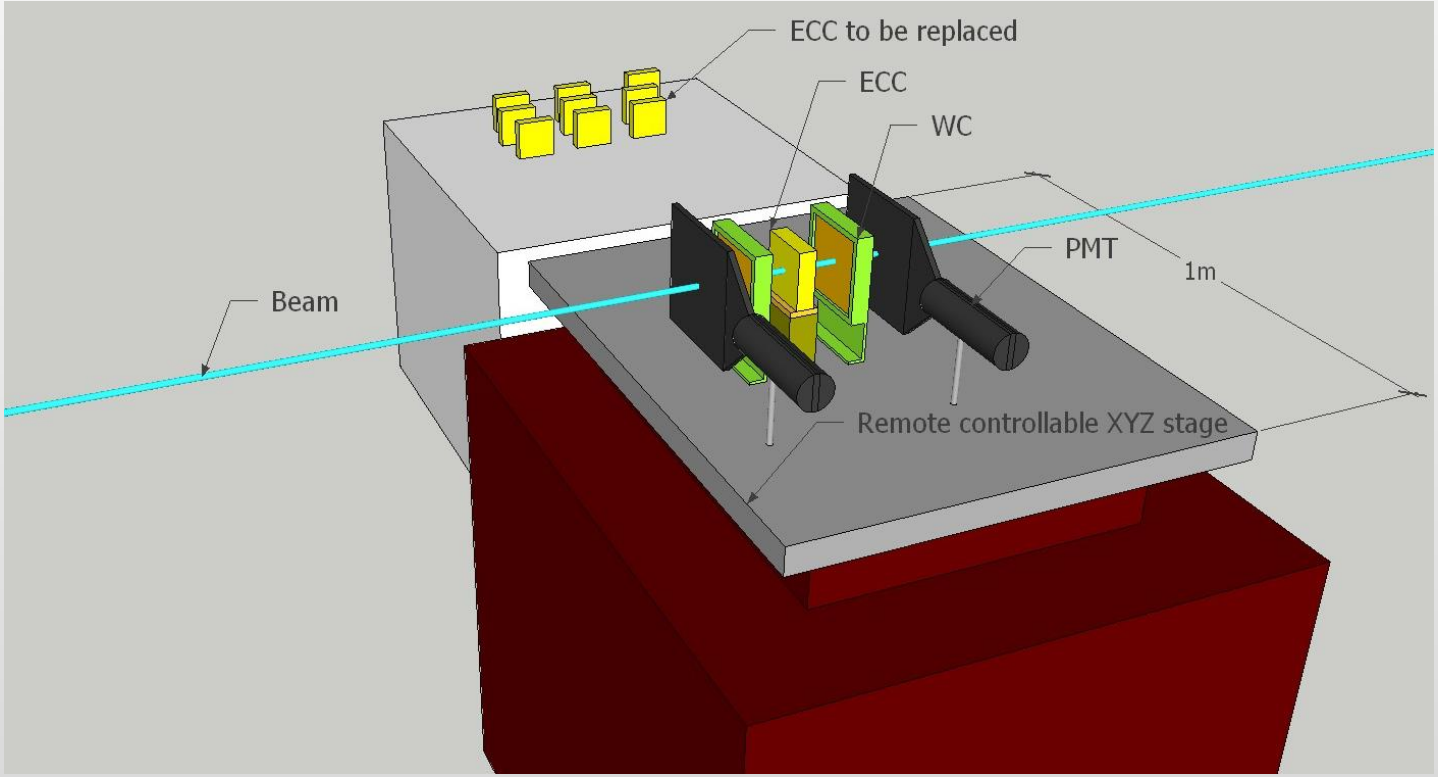
- In case of 10 units → 0.05 λ_{int} in tungsten → 4x10^9 pot needed to get 2x10^8 proton int.
- Track density in emulsion: keep <10^5 tracks/cm^2 at the upstream side
- To expose 4x10^9 pot → detector surface 4x10^4 cm^2 (400 modules)







The expected setup of the experiment



Old design

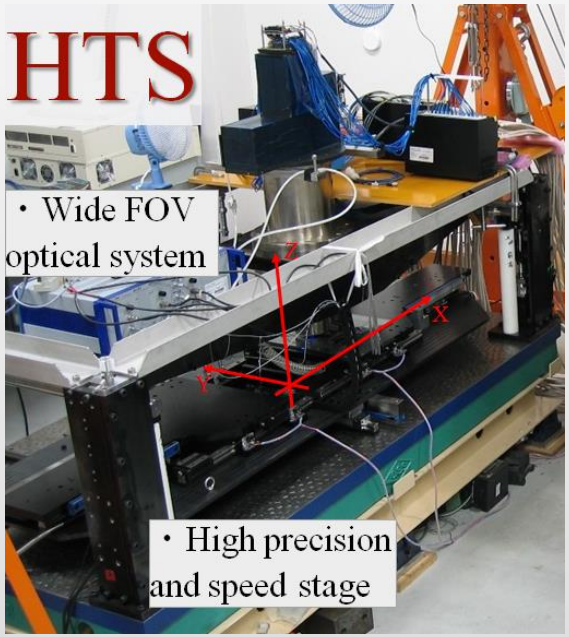
Needed beam time

- Assuming 10^5 protons/spill and the beam spot 1 cm^2,

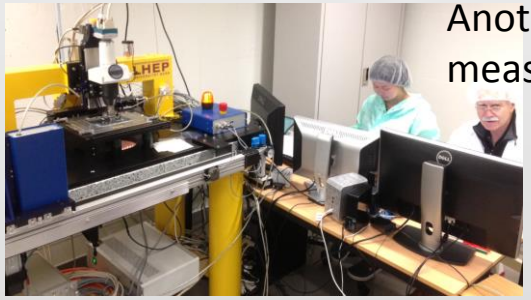
detector surface 4 x 10^4 (cm^2) x 30 (sec/cm^2) = ~2 weeks.

- Module exchange time: 10 min x 400 modules = ~ half week.

Readout of emulsion data



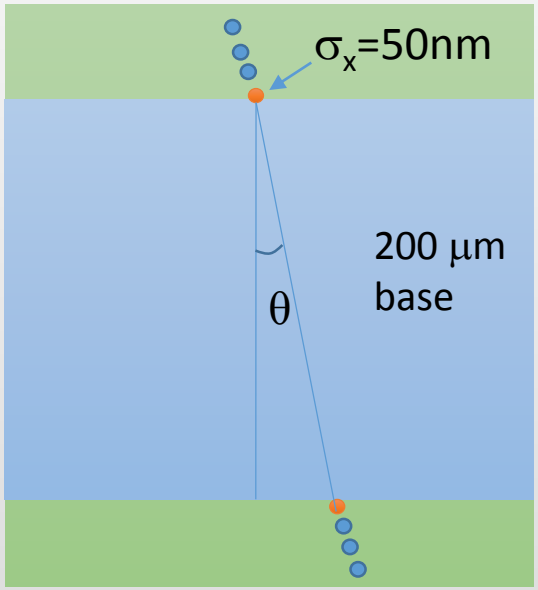
← New scanning system being developed in Nagoya, aiming at the speed of 9000 cm^2/h (22 m^2/day)



Another system dedicated to high precision measurements to be developed in Bern

	New experiment
Emulsion surface	~500 m^2 (x2sides)
Readout time	Standard scan 4 months to 1 year
	High precision scan ~3 month

High precision measurement system



- Intrinsic resolution of each grain = 50 nm
  - Two grains on top and bottom of 200 μm base → **0.35 mrad**
- Conventional systems spoil it due to mechanical vibration of Z axis (about 0.2μm, corresponding to 1.5 mrad)
- → Need high precision Z-axis
- Piezo objective scanner under testing → Z axis systematics to be kept below 60 μrad (0.06 mrad)
- By fitting a series of grains, the angular resolution would reach **0.2 mrad**

Piezo objective scanner

- Angular alignment between films to be done by using dense 400 GeV proton tracks
  - 400 GeV proton scatters 2 μrad between emulsion trackers
  - 10^5 tracks/cm^2 = 100 tracks in each microscope view

Prototype test experiment in 2016

- Proton beam test in Nov. 2016
  - 5 days of beam time at the H4 beam line
  - 20 m^2 emulsion surface (1:20 of the final setup)

- Aim
  - Test of tuning the beam size
  - Optimization of the setup
  - Proof of principle of the experiment
  - x_F evaluation by ~30 detected $D_s \rightarrow \tau$ events

Several conditions

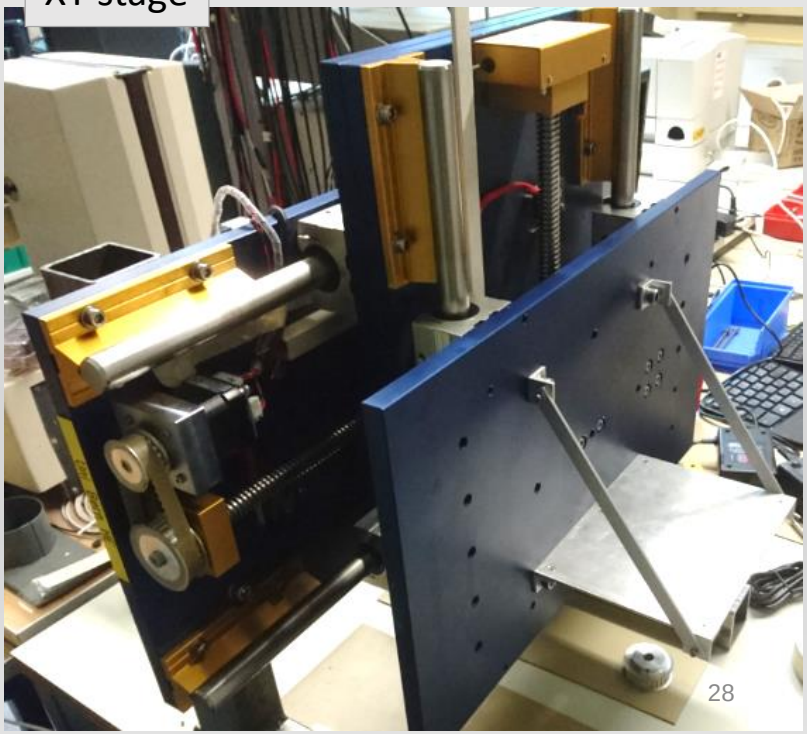
- Track density study
  - 10^4 / cm^2 x a few bricks
  - 10^5 / cm^2 x ~10 bricks
  - 10^6 / cm^2 x a few bricks
- Longitudinal thickness
  - 5, 10, 20 units (50, 100, 200 films)

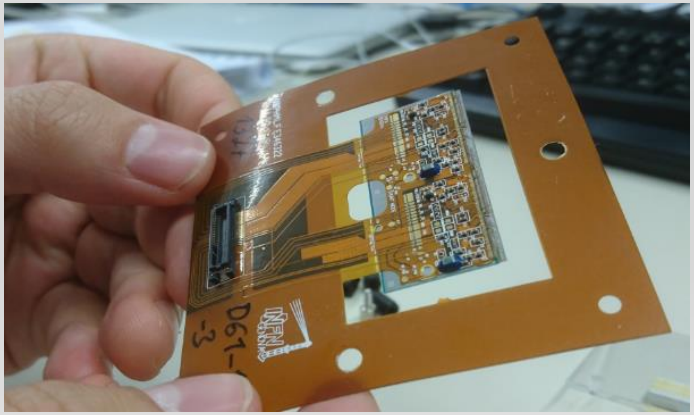
Preparation in progress

- Emulsion film production in Bern using the gel from Japan
- Target mover: XY stage and control
- Beam profile monitor with silicon pixel sensors (~4cmx4cm)

Establishing the film production facility equipped with 9 gel pouring tables

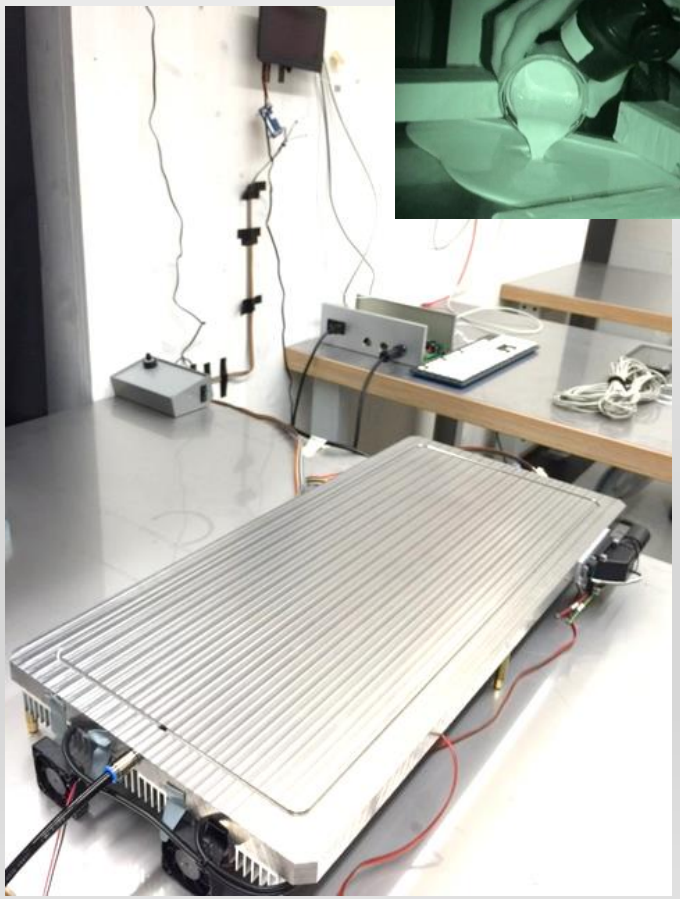
XY stage





Film production in Bern

Total 20 m^2 double-side coated films (1600 small-size films)
Plan: 0.15 m^2 / table x 9 pouring tables x 4 production batches / day



Emulsion layer (top)
Plastic base
Emulsion layer (bottom)

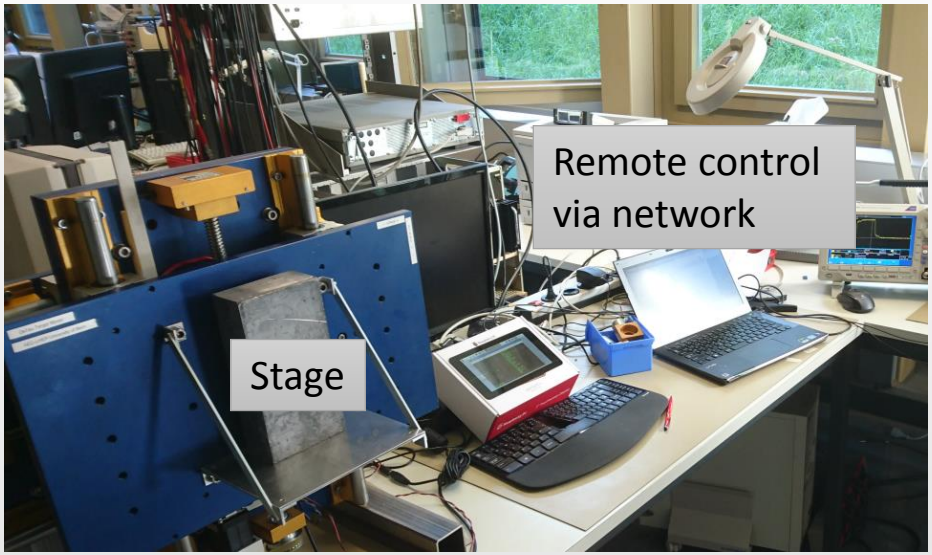
Pour emulsion gel on plastic sheet
(60 cm x 25 cm = 1500 cm^2 per table)

← 8 more tables are being installed

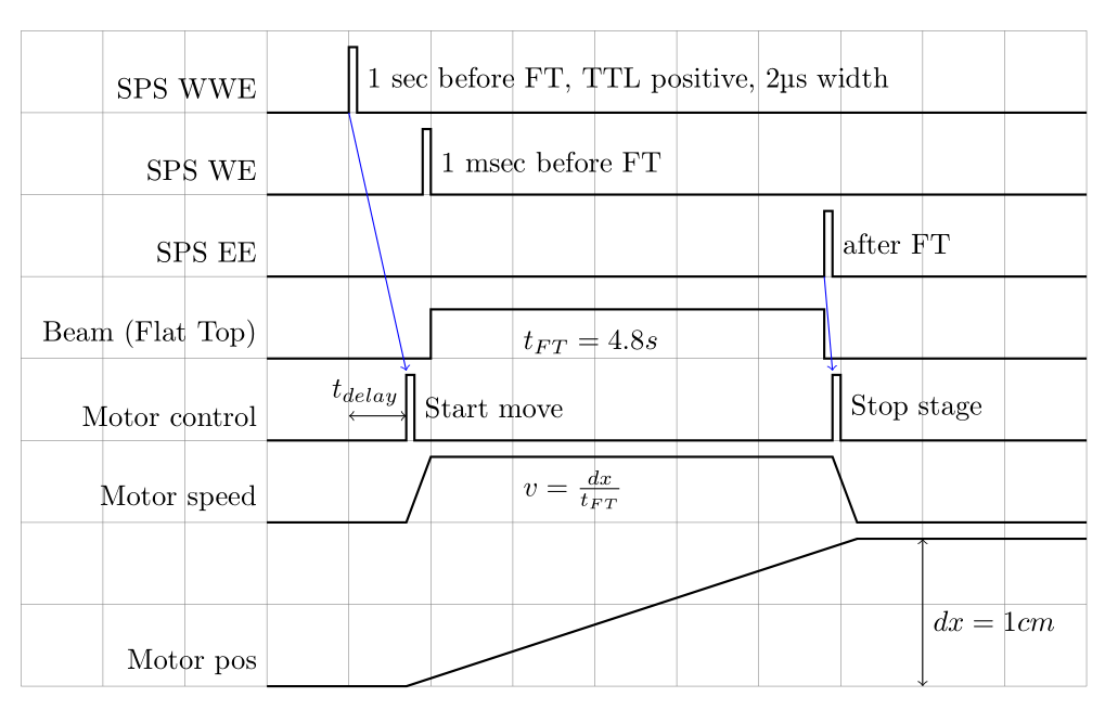
Maximum speed of 10 m^2 per week
will be achieved with this system

Target mover: XY stage and control

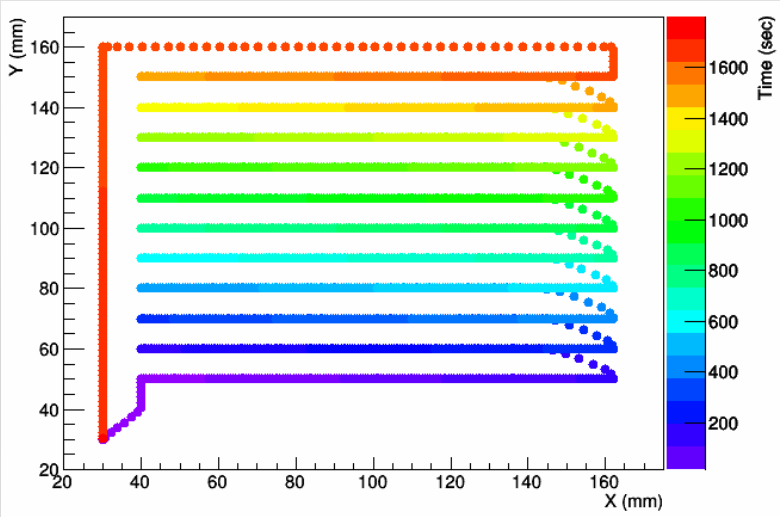
Move the modules w.r.t. the beam for uniform irradiation with a density of $10^5/cm^2$



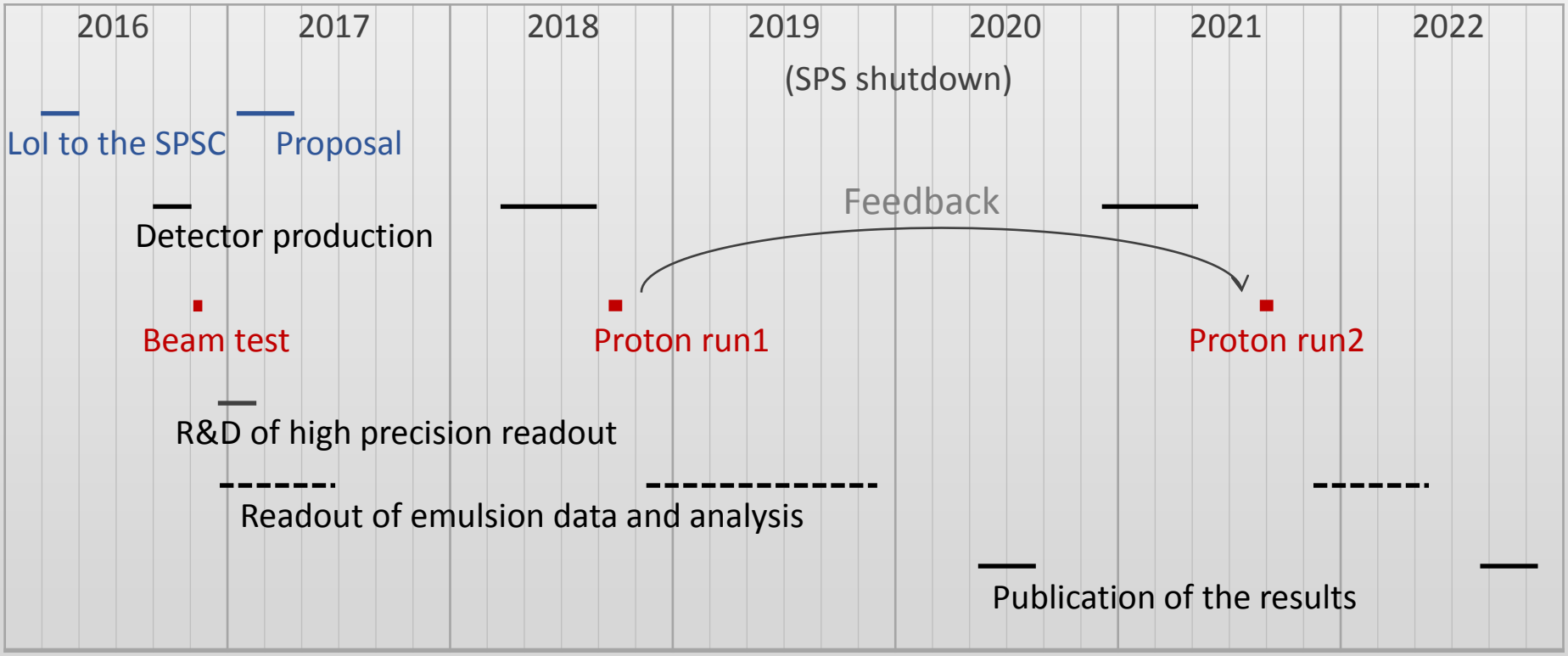
Timing chart



Moving test



Timetable of the whole project



Summary and prospects

- ν_τ CC cross section measurement could be a test of lepton universality
  - ν_τ cross section measurement have been reported only by DONUT
  - The DONUT results suffer from large systematic error (>50%), not only statistical error (30%)
  - The main systematic error is how D_s were produced at beam source

DsTau project

- $D_s \rightarrow \tau \rightarrow X$ precision measurement in high energy proton interactions is essential input toward precise evaluation of ν_τ cross section
- 2×10^8 proton interactions are to be obtained to analyze 1000 $D_s \rightarrow \tau \rightarrow X$ events

- Prototype test experiment in Nov. 2016
- Aiming to realize the experiment hopefully in 2018 before the SPS shutdown