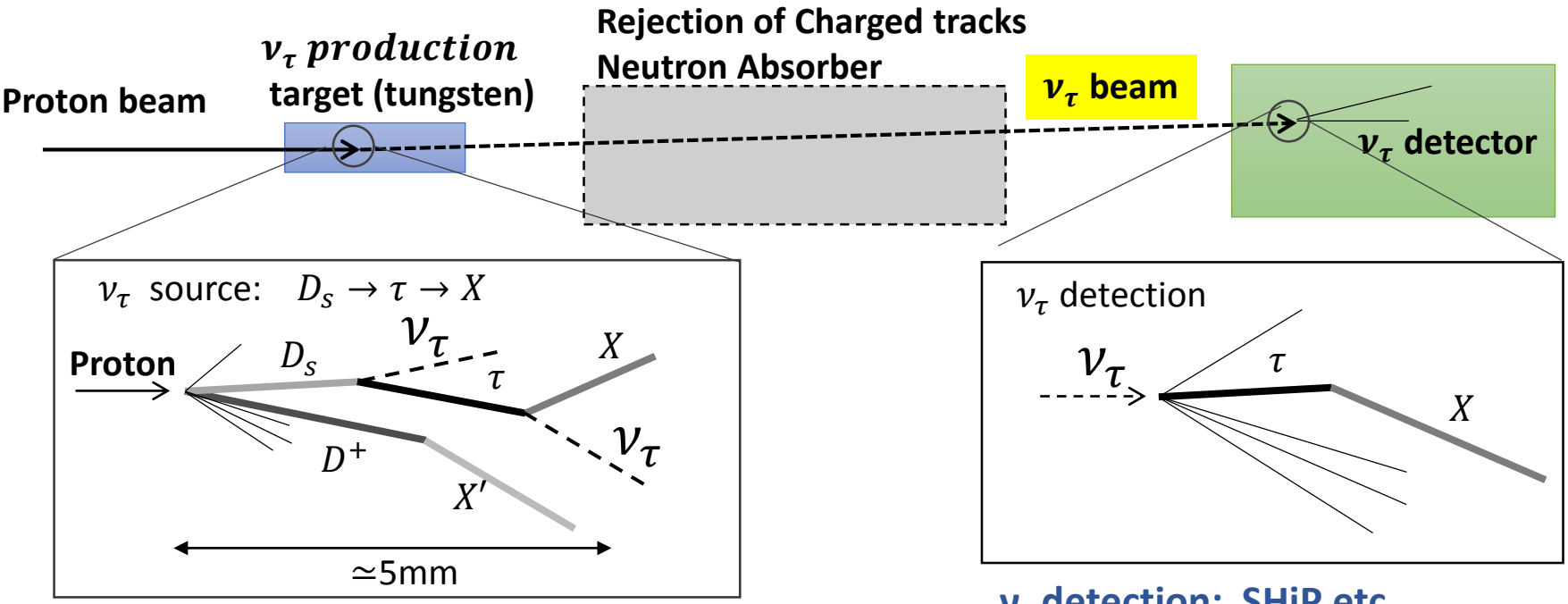
Study of tau neutrino production with nuclear emulsion at CERN-SPS

Osamu Sato (Nagoya University)

for the DsTau Collaboration

Tau neutrino cross section measurement
- concept -



ν_τ production study: DsTau

- **No data of Ds differential production cross-section**
- **Larger ~50% uncertainty of ν_τ flux**

ν_τ detection: SHiP etc.

- 9 **ν_τ** detected by DONuT (bam **ν_τ**). 33% statistical error
- 10 **ν_τ** detected by OPERA (Oscillated **ν_τ**)
- SHiP ~ 10000 events a few % statistical error

DsTau Experiment (CERN NA65) Physic motivations

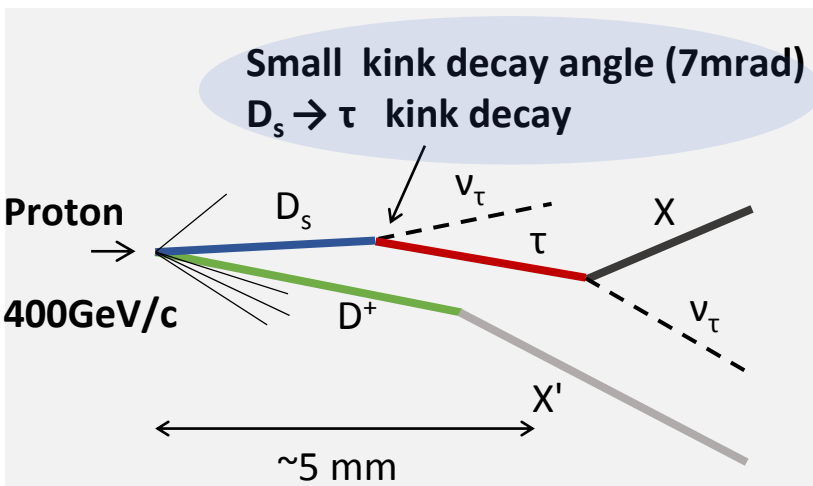
1. Precise understanding of ν_τ production flux

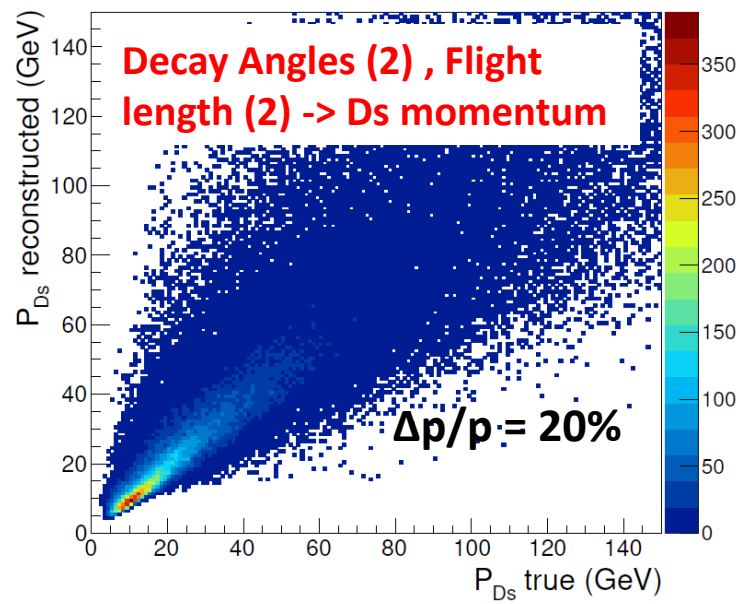
Measurement of differential production cross section of Ds .
Using a specific decay topology :: Ds->tau->X (double kink) decay .

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

x_F : Longitudinal momentum (Pl) / Pl_max
Pt : Transverse momentum

Ds->tau decay angle is small as average 7mrad in flight length a few mm .
Using Sub micron spatial resolution 3D tracker :: Nuclear emulsion tracker .





DsTau Experiment (CERN NA65) Physic motivations

1. Precise understanding of ν_τ production flux (cont.)

Reduction of $\nu\tau$ nucleon cross section uncertainty 50%→10% **.**
For re-evaluation with updated $\nu\tau$ flux for DONUT
For input for future experiment SHiP $\nu\tau$ program etc .

The detected 1000 Ds->tau->X events for the uncertainty reduction
A total of **$2x10^8$ proton interactions will be analyzed** to hand detected 1000 Ds->tau->X .

2. Understanding of charm production

Several 10^5 events having pair charms among proton interaction products.

The angle (θ, ϕ) correlation of the pair charm particles for event by event , etc .

X_F distribution for Charged and Neutral charm respectively.

Analysis about Charms produce into Forward direction :: intrinsic charms (valence quark like c) exist ?etc .
into "Backward direction (soft Charm production region) "

3. Understanding of proton interaction

Plenty of proton interactions .

Interaction with several Materials (Tungsten, Molybdenum , Nuclear Emulsion, Plastic) .

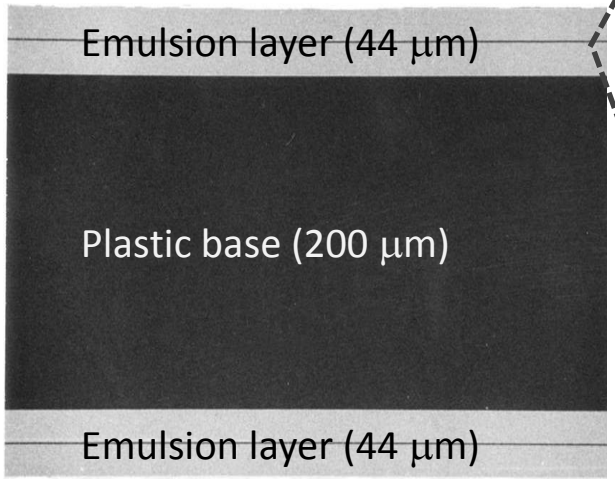
Charged track's angle (rapidity) and momentum distributions .

Nuclear Emulsion detector:

3D tracking device with 50 nm precision

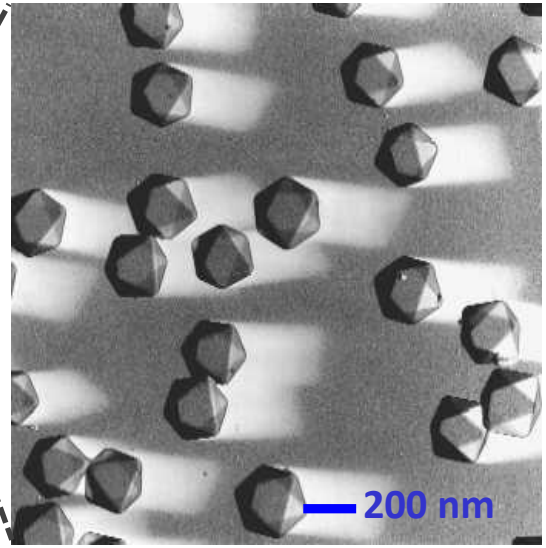
Emulsion film

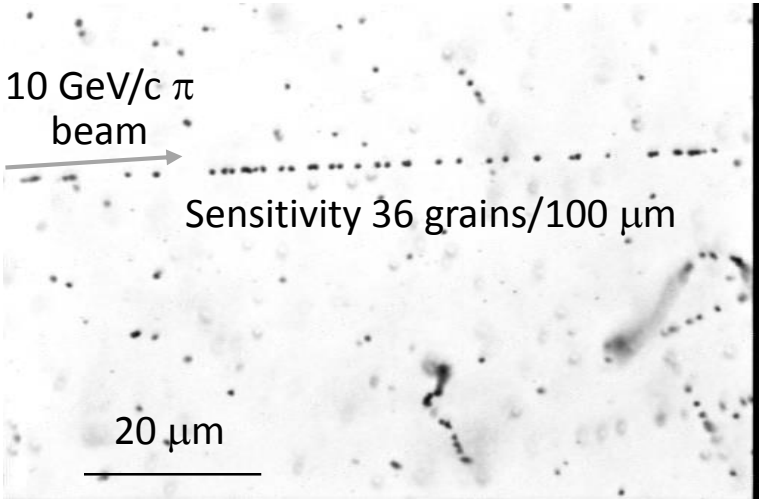
Cross-sectional view

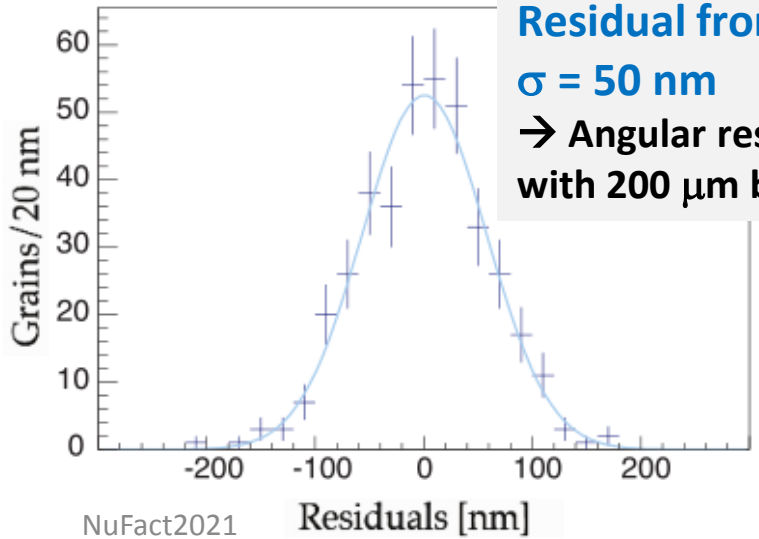


AgBr crystal

10^{14} crystals in a film







Residual from fitted track

σ = 50 nm

→ Angular resolution 0.35 mrad with 200 μm base

DsTau loadmap

Pilot run 2018 Aug. @H2
Accumulated ~**1.8 · 10^7** interactions

Test beam 2016
- Test of the detector structure

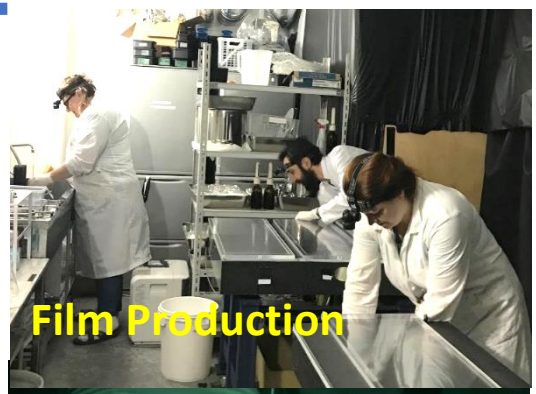
Test beam 2017
- Improved detector structure
- Refine exposure scheme

Pilot run 2018
- **1/10 of the full-scale experiment with tungsten target .**
- **ν_τ flux ~30% uncertainty**
- **Revise the DONUT result**
- **Charm physics**

Now

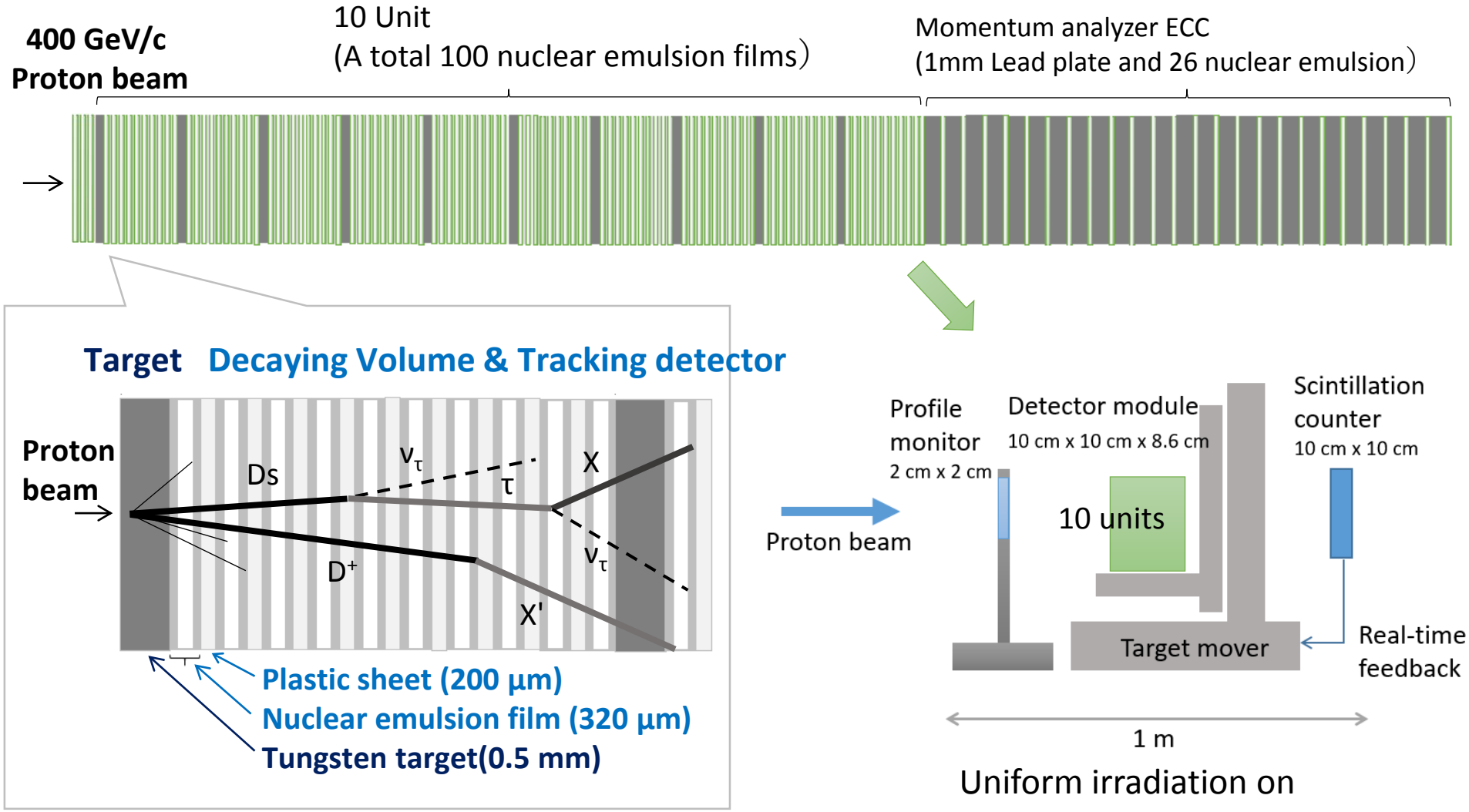
Physics run 2021-2022
- **Full scale experiment with tungsten and molybdenum targets**
- **Aiming detect 1000 $D_s \rightarrow \tau \rightarrow X$ events**
- **ν_τ flux~10%**

Approved as NA65



The detector structure (~400 modules)

2.3×10^8 Proton-tungsten interactions (4.6×10^9 POT)



Uniform irradiation on detector surface x,y

Tracks readout from Nuclear emulsion & Analysis .

Total ~4000 films

Nuclear emulsion prior treatment for scanning .

Surface cleaning, Thickness control.

400-800films/month

① Full surface scanning

~300 films/**month**

~700 films/month (with night shifts)

② Ds -> τ search

Precise measurement for Small angle kink (~ 7 mrad)

Hyper Track Selector (HTS)

Track readout speed 0.5 m²/h/面

Angle resolution ~2 mrad

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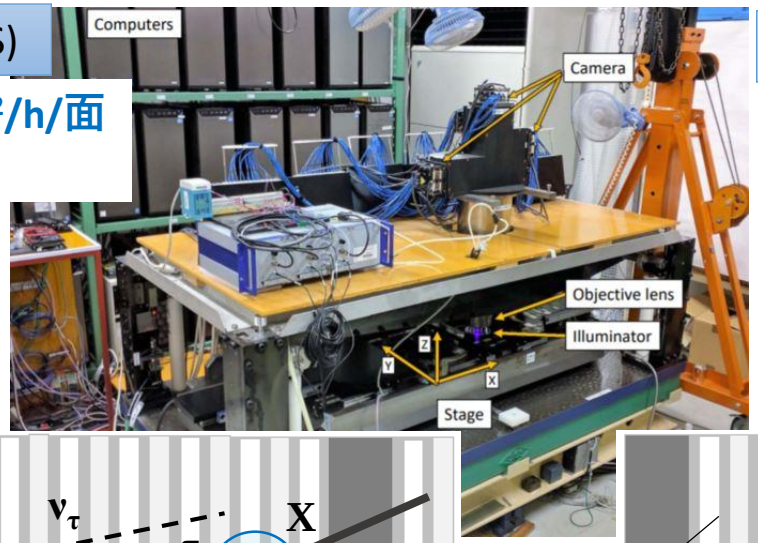
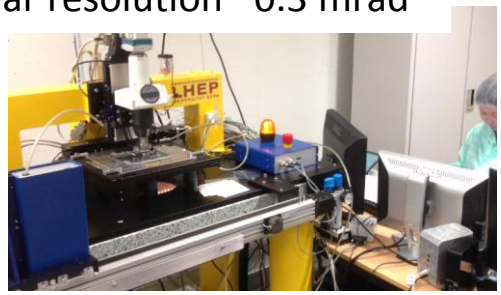
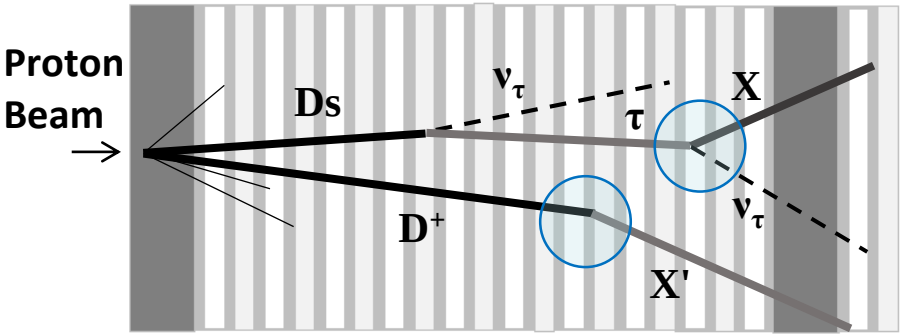
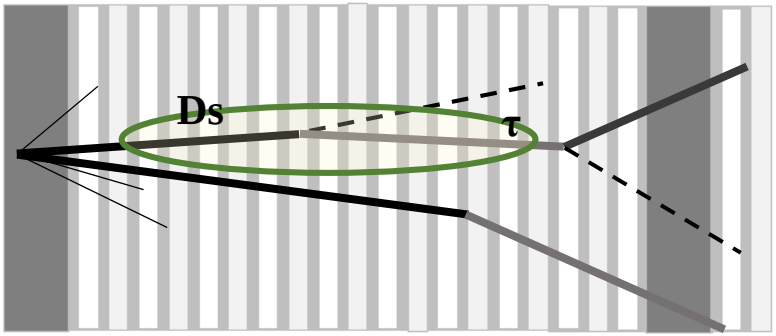


Dedicated microscopes

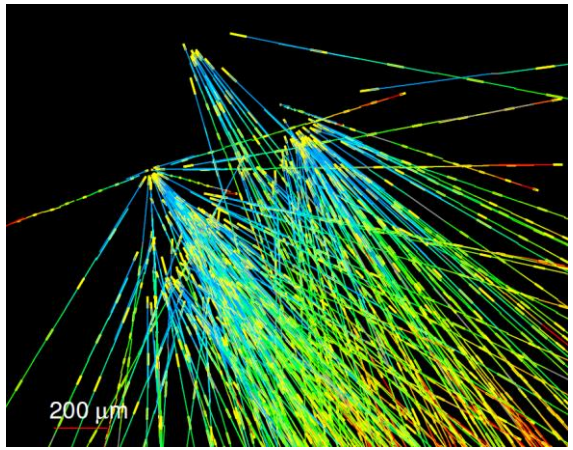
Angular resolution ~0.3 mrad



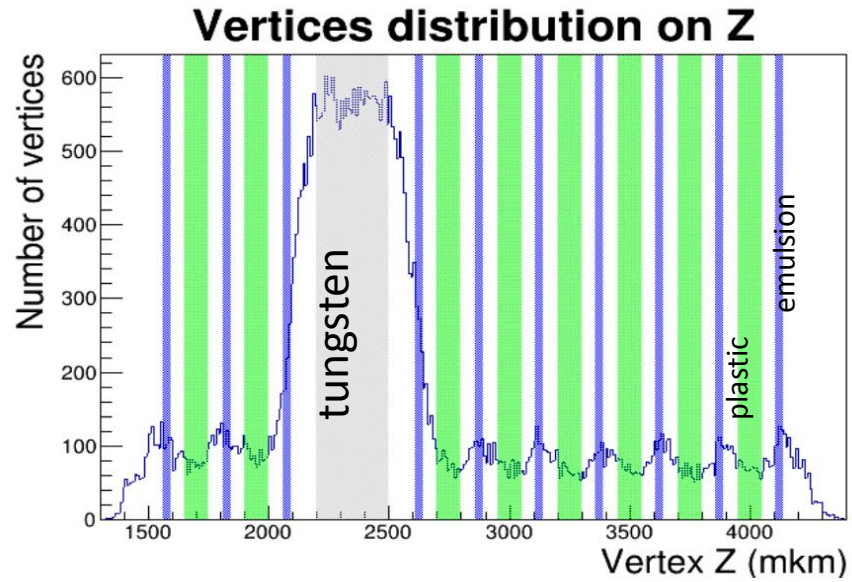


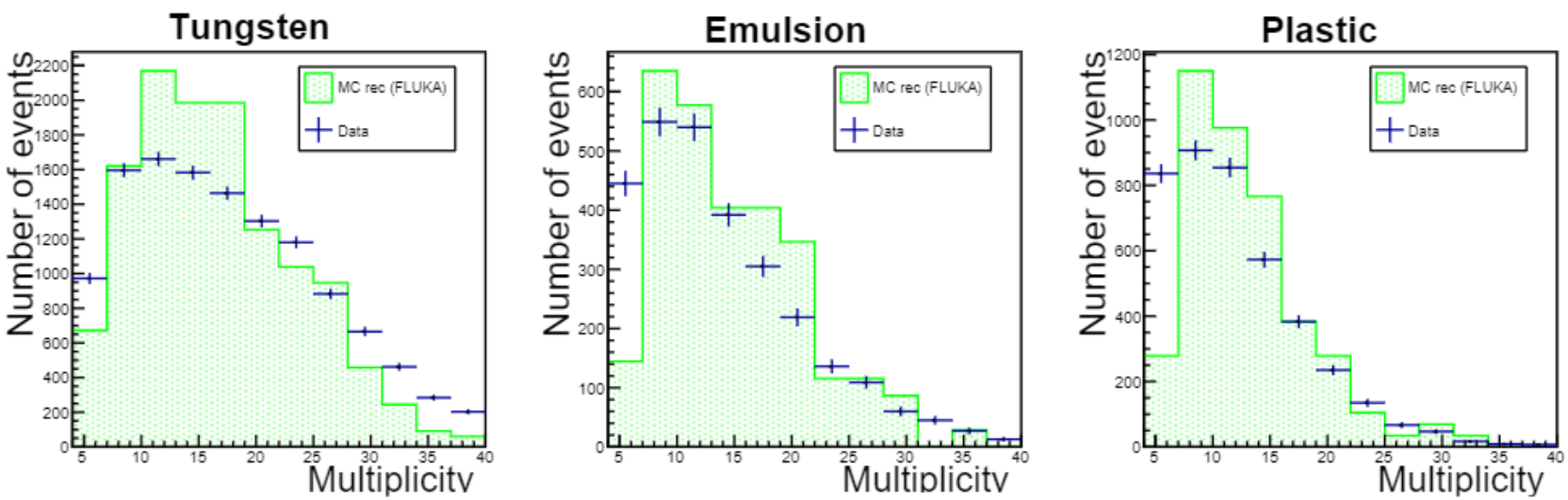


Proton-target nucleus interaction



Interaction density par a tungsten plate ~500/cm

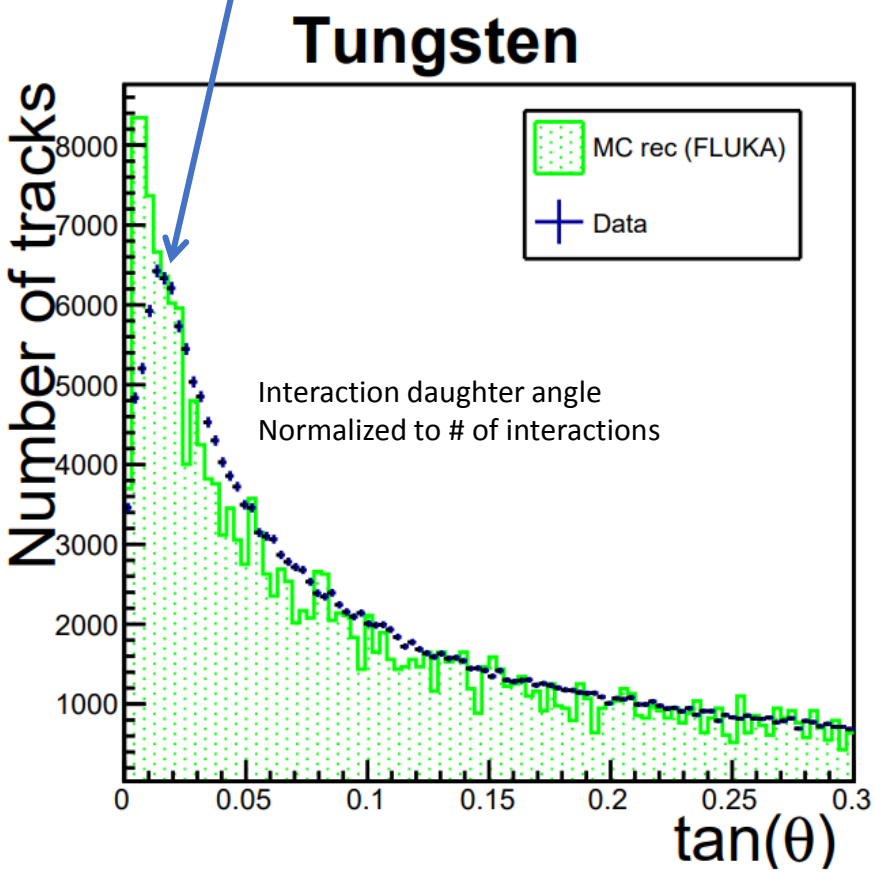


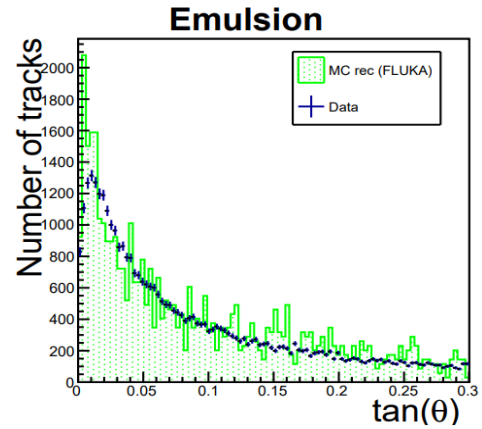


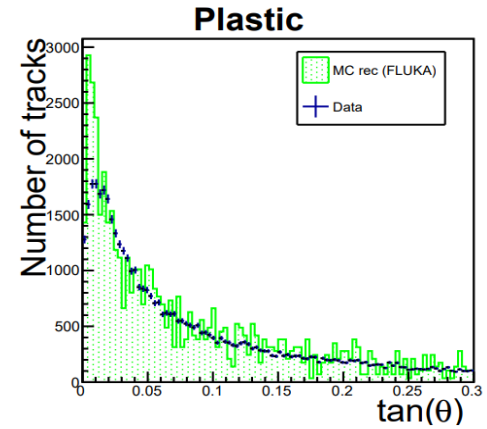
Multiplicity distribution of several materials

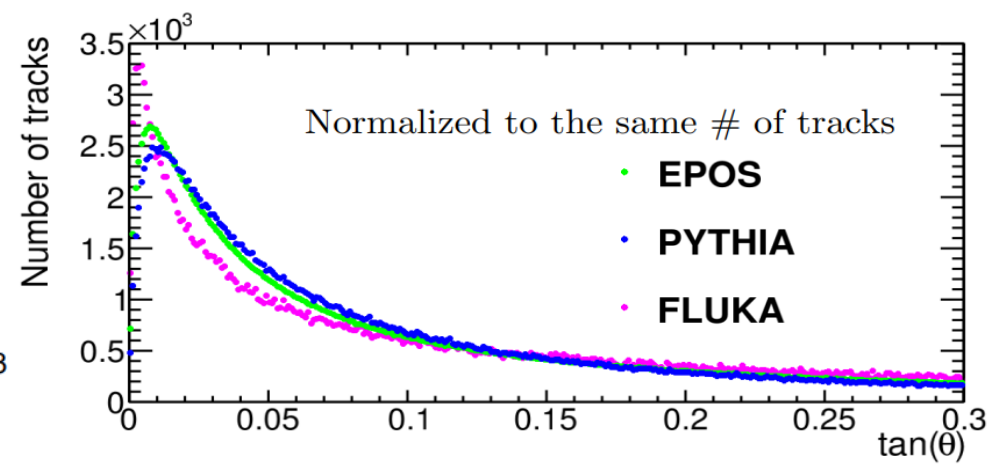
Angular distributions of proton interaction

- General distribution agrees with the FLUKA prediction.
- A deficit of forward angle (<20 mrad or $\eta > 4.6$) is observed.
- Comparisons between other generators are ongoing.

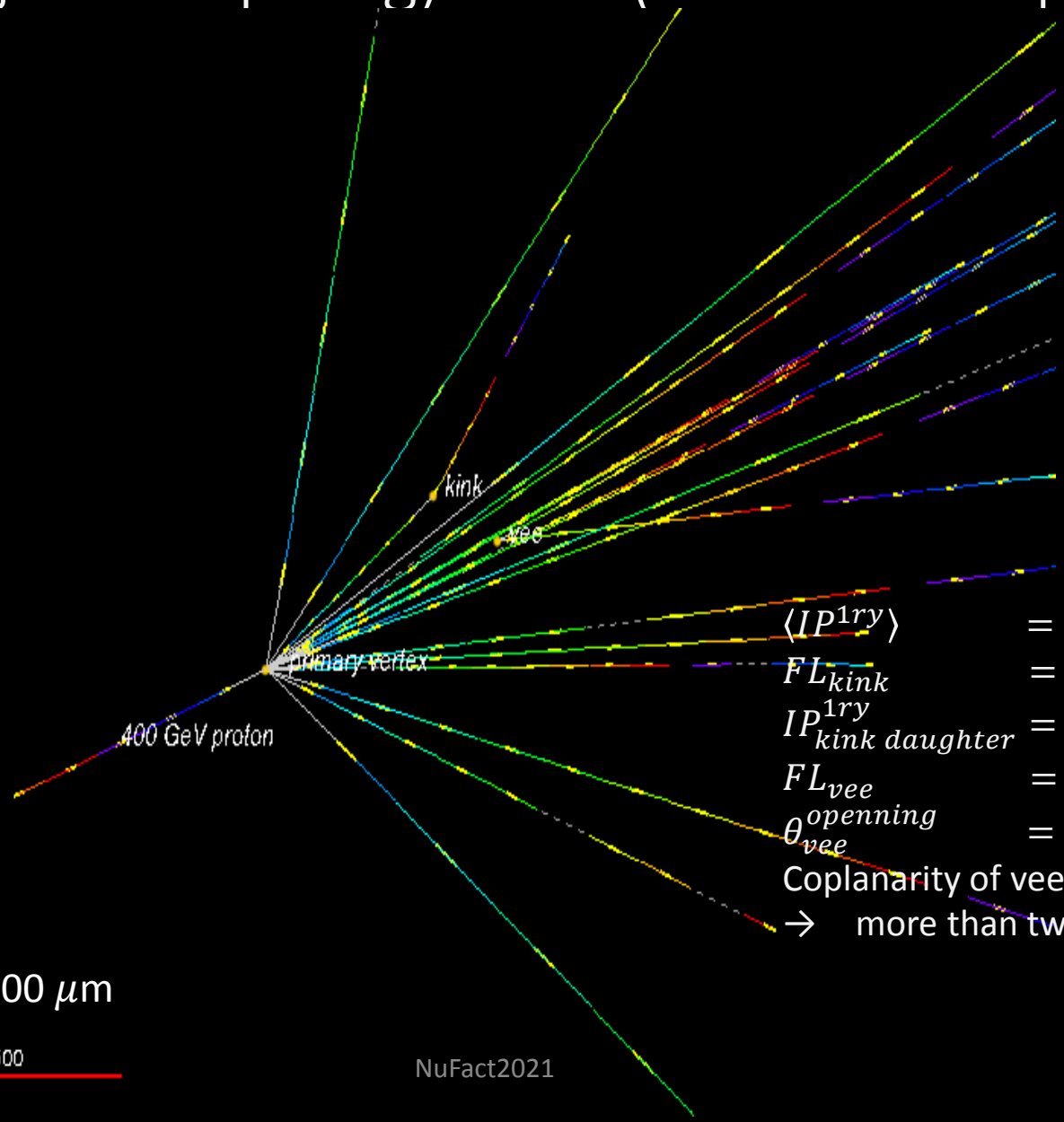








Example of an event with Charm Pair cand.
Kink(Charged one prong) + Vee(Neutral two prongs)



$\langle IP^{1ry} \rangle = 1.6$ 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

→ more than two bodies decay

500 μm

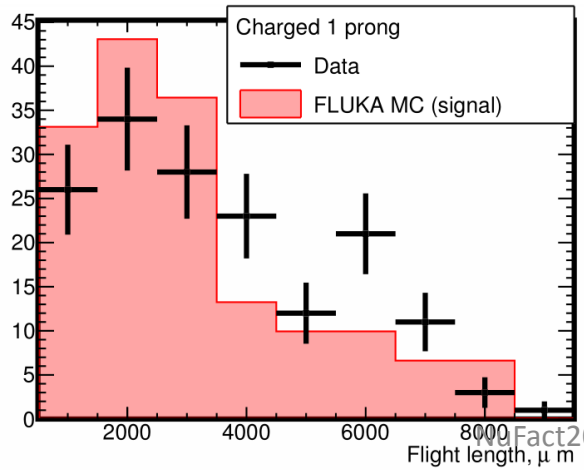
500

Search for events associating a charm pair

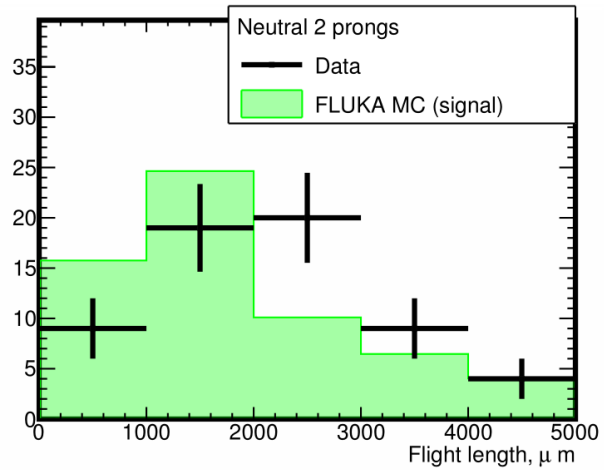
- **3.4253301 x 10^7 injected protons (2% of Pilot run) were analyzed**
- **2.72120 x 10^5 proton interactions (1.47236 x 10^5 tungsten int) detected**
- **159 (115 tungsten int) events with charm pair**
- **Currently increasing statistics (next page) with tunning selection parameters.**
- **About to start to small angle kink search.**

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

Flight length of Charged Charm cand.



Flight length of Neutral Charm cand.



Updating the analysis statistics

Currently mass processing for event vertexing , decay search is performing .
So far 18 times sample compared to previous page were processed .
Semi-automatically done up to selection of events with double decay vertices .

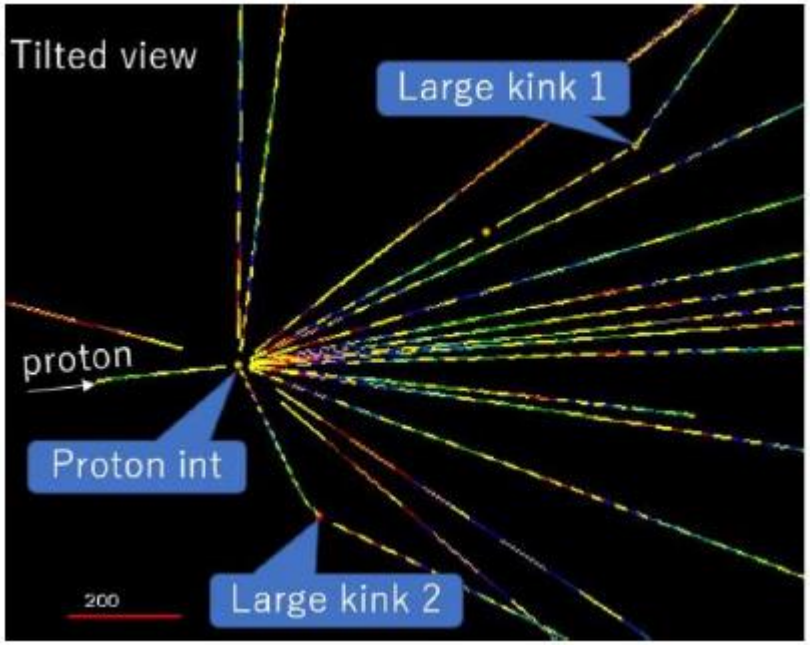
The dedicated charm decay validation will be done .

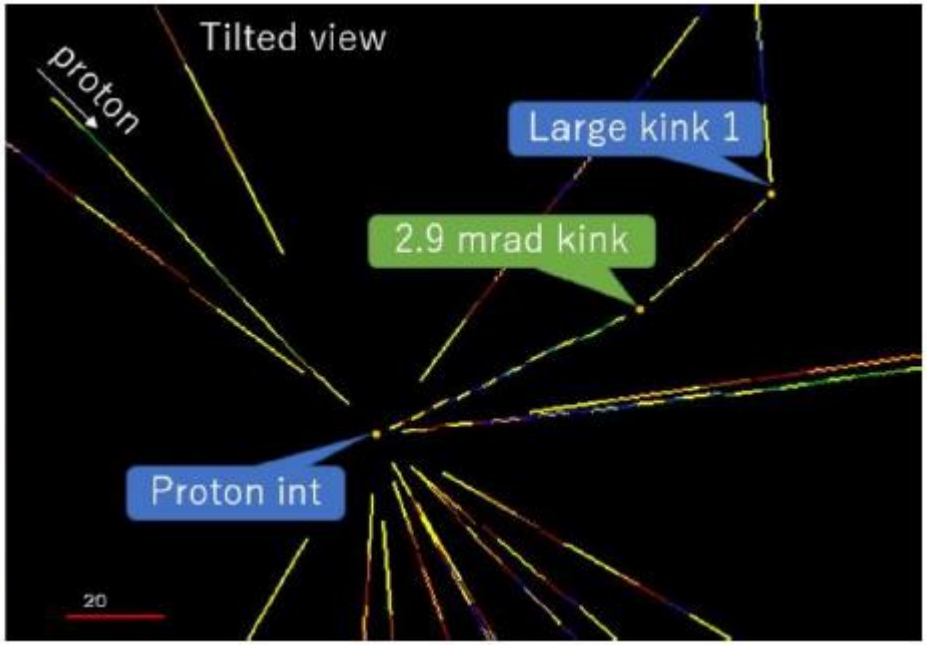
- Event Display checks
  - rejection of secondary interaction by checking additional track existence.
- Kinematical analysis
  - Momentum of decay daughters will be measured by angle difference between materials by Multiple Coulomb Scattering.
  - Rejection of single scattering due to low momentum .
  - Cut secondary interactions by decay transverse momentum (<100 MeV/c) to be tuned.

Analyzed sample/ 2018 pilot run	**22.2%**	
Protons on tungsten plates	486,137,516	
Vertices in tungsten plate	2,653,846	18 x previous report
Double decay vertex candidates	17,574	To be dedicate checked

Some small angle kink detection

- We started small kink hunting for already observed two decay topology events.
- The parent track making “Large kink” is checked whether small kink is hidden in the series of track segments formed the parent track or not.
- After tuning parameters for cuts, mass checks will be come soon.





Schedule
Physics run(NA65) in 2021 -2022

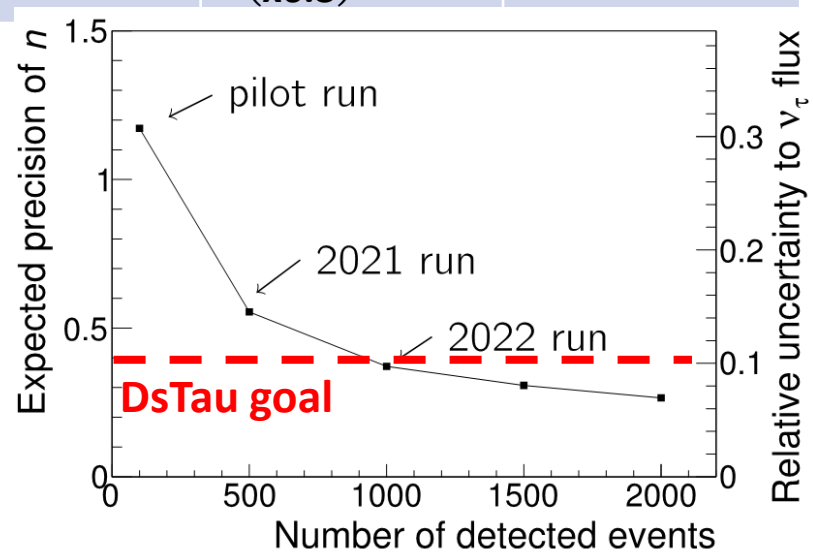
2016 test beam exposure
- Test for detector structure

2017 test beam exposure
- Improvement of detector structure
- Improvement beam exposure scheme

2018 Pilot run
- **1/10 accumulation events scale**
- **ν_τ flux～30% uncertainty**
- **DONUT update ν_τ cross section**

2021-2022 Physics run
- **1000 detected $D_s \to \tau \to X\,\nu_\tau$**
- **ν_τ flux uncertainty～10%**

	detector modules	Nuclear emulsion(m^2)
Pilot run 2018	30 (=1)	49
Physics run 2021	**150 (x5)**	**246→ 100**
Physics run 2022	**190 (x6.3)**	**312→ 458**



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

- Two weeks beam per year
- Beam time 2021 Sep22 to Oct06.
- Smaller size than original schedule due to COVID19.

Summary

- The **DsTau** aims to study **Ds -> tau -> X** differential production cross section at **400 GeV/c p**- tungsten int.
- **Nuclear emulsion tracker for Ds->tau small kink (~7mrad) detection in short range(~mm) .**
- **Pilot run in 2018 and Physics run 2021, 2022**.

- A total of **$2x10^8$** proton-tungsten interactions will be analyzed.
- Detecting ~**1000** Ds->tau->decays will reduce uncertainty on **$\nu\tau$ flux to 10%.**
- During the main analysis ~**10^5** Charm pair associating proton interaction will be collected and Properties of Charm pair production will be studied in detail
- **Proton interaction with right (CH), medium (Ag,Br), heavy (W, Mo) nucleus**, can be studied in detail.

- **The 2018 pilot run analysis**

  The mass processing is running and about 22% of fiducial volume were done so far **.**

  2.65×10^6 p-tungsten int. collected, dedicated analysis will be done for double decay topology candidates.

  Small angle (Ds->tau decay) hunting is about to start after tunning selection parameters.

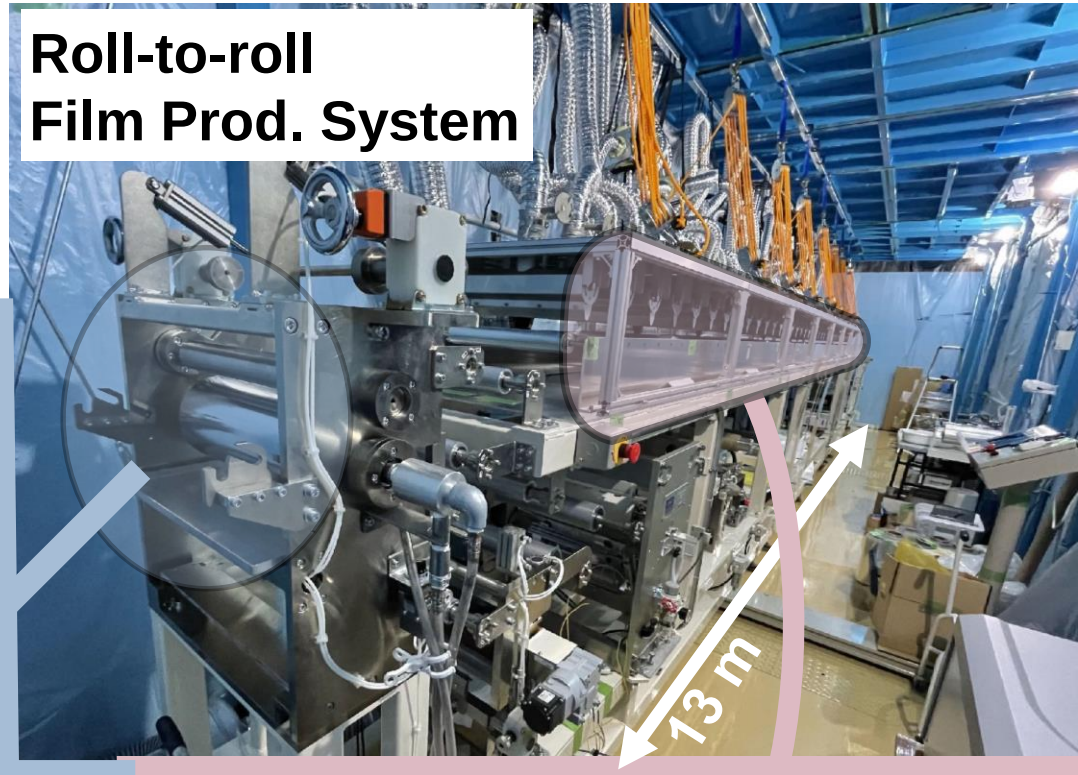
- **The 2021 physics run**

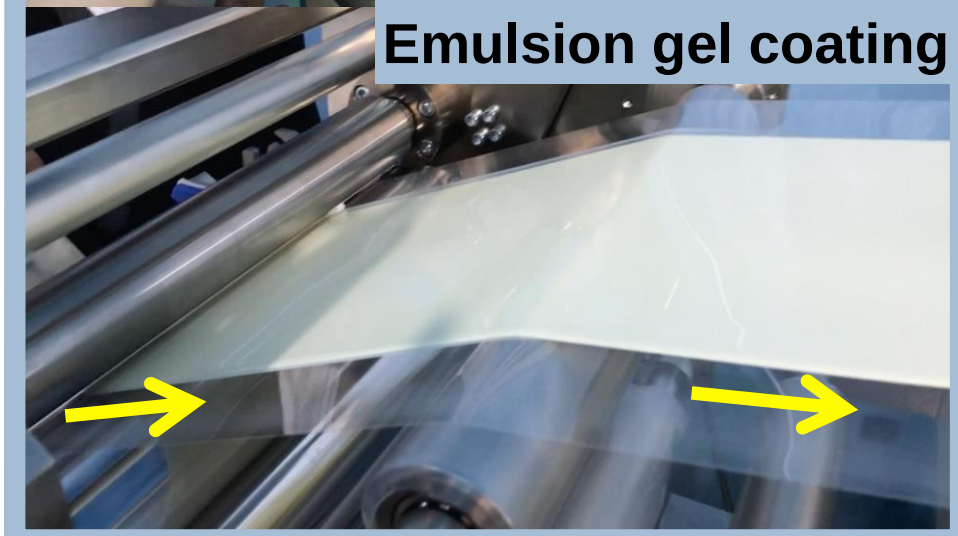
  CERN SPS 400 Gev Proton beam exposure very soon, **beam time Sep22 to Oct06**.

Backup

Film Production Facility (Nagoya Univ.)

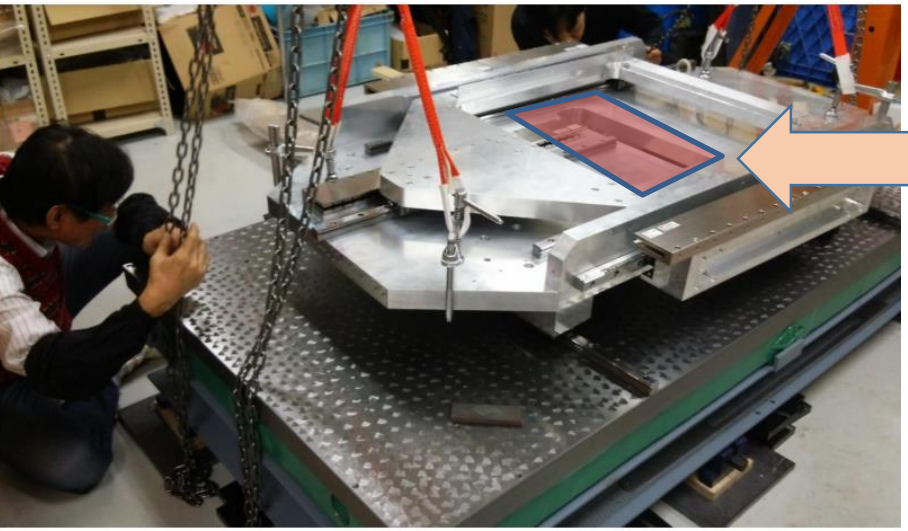
Facility construction was completed at the end of 2020. Production test is ongoing.



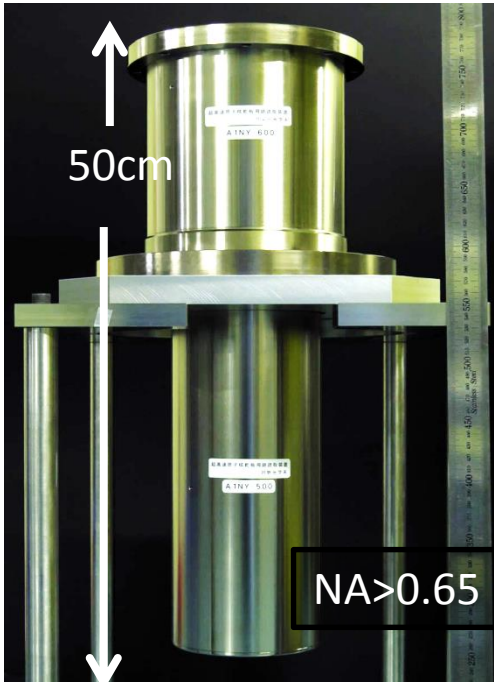


New Scanning system @Nagoya University : **HTS2**

- **2.5 m²/hour, 5 times scanning speed of HTS**

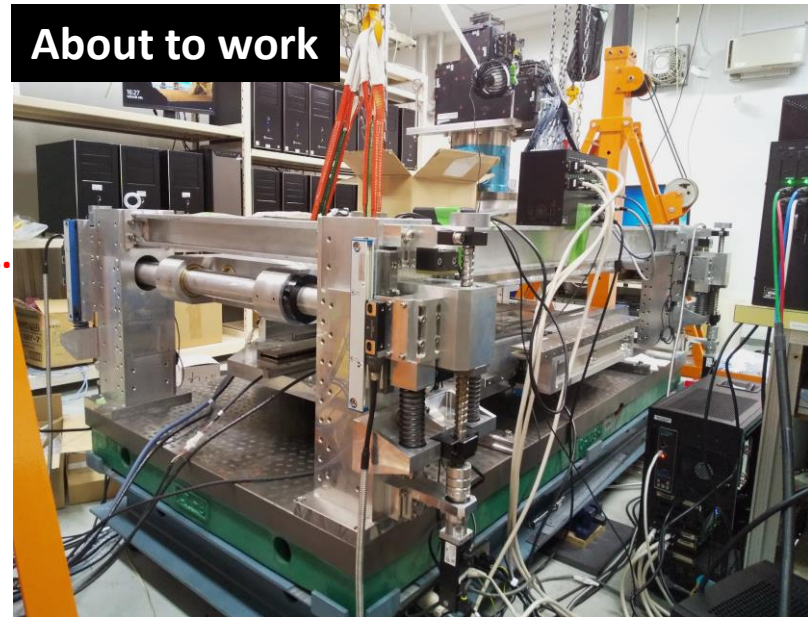


- **Larger working area : 30cm x 40cm**
- **Larger FOV : 9.33 x 5.25 mm²**
- **Continuous scanning (not stop & go)**

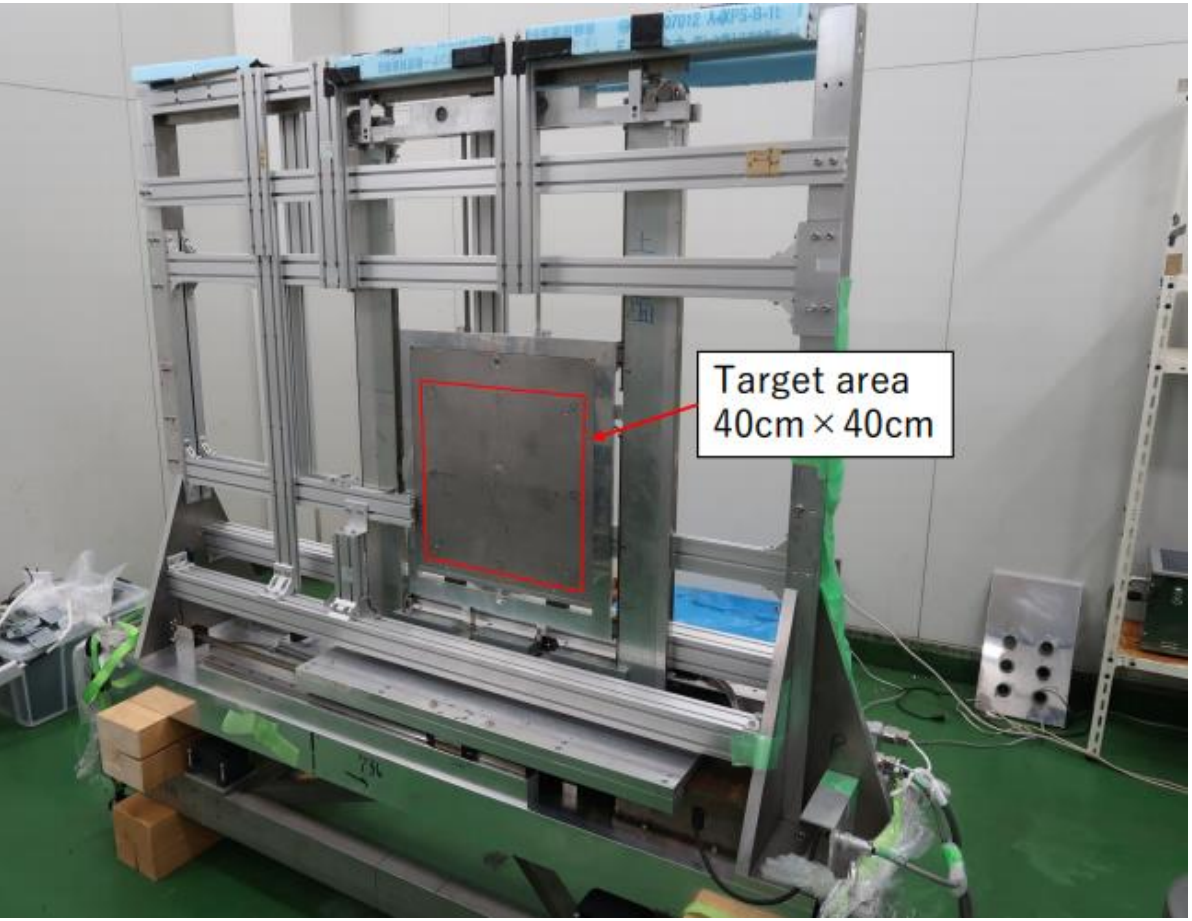


→ Total film area of 2021, 2022 physics run is 11 times that of 2018 Pilot run.
And 2018 Pilot run films scanning was done in 17 months.
So about 1 year to readout for each physics run films using HTS2.

About to work



Target mover prepared for Physics run



We changed detector area size
12.5x10cm2 → 25x 20cm2
to scan emulsion film quickly.

Target mover used for other exp
(J-PARC E07) is tunned for DsTau
beam exposure .

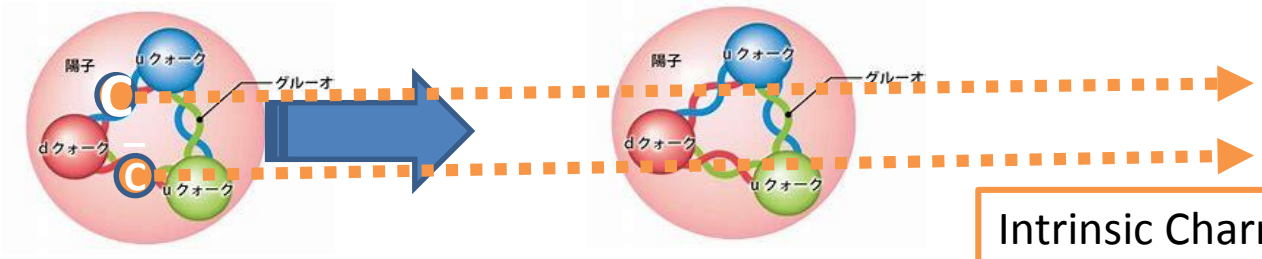
Shipped from Japan to CERN

Intrinsic (valence quark like) charm ??

Two case could be considered and both cases can be analyzed in DsTau.

1）Intrinsic Charm in beam proton.

The Charm became forward going high energy .



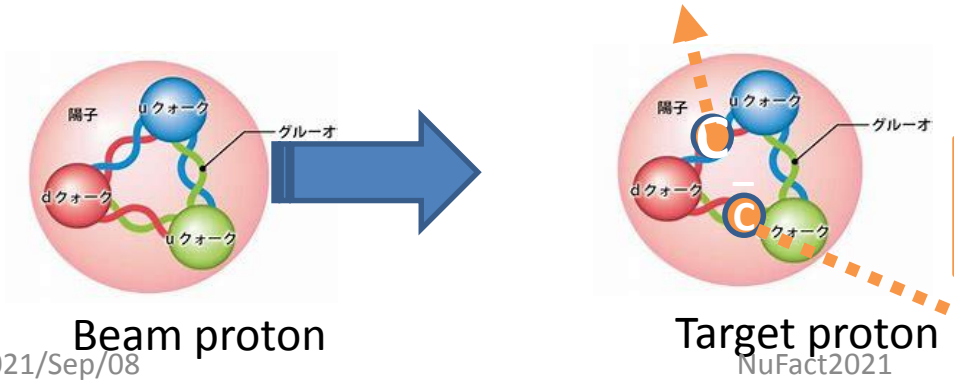
Beam proton　　Target proton

Intrinsic Charms
Carry significant part of
beam proton's momentum

2）Intrinsic Charm in target nucleon.

It would be a soft Charmed hadron.

Could it be captured in the target nucleus (ie. Charmed Hyper Nucleus) ?



Beam proton　　Target proton

Intrinsic Charms in Soft production
Fermi momentum + α ??

Tau neutrino interaction cross section

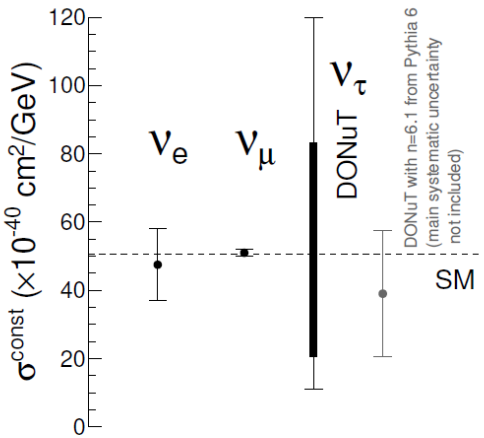
The property of ν_τ is least known among active neutrinos .

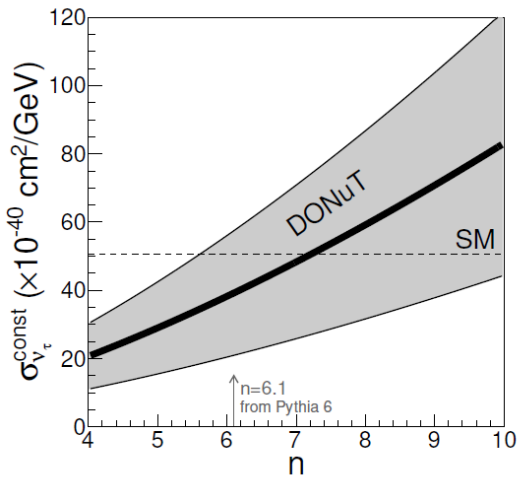
Is the lepton flavor universality kept also neutrinos ?

Large error on ν_τ cross section measurement so far.

New physics effect could be hidden in the error .

Also for input for future neutrino oscillation analysis or cosmic neutrinos .





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

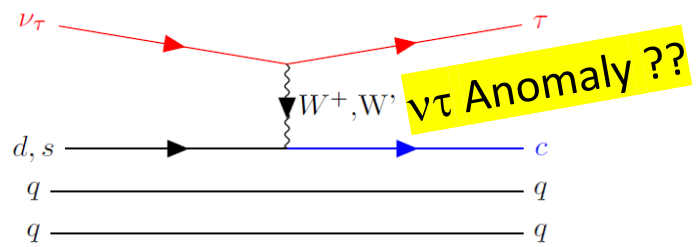


Figure 1 ν_τ CC charm production

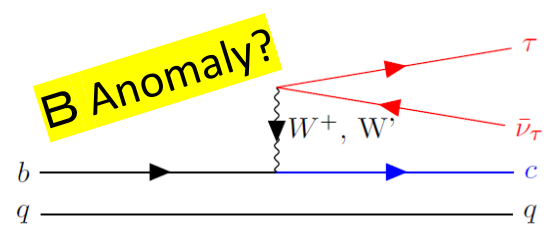
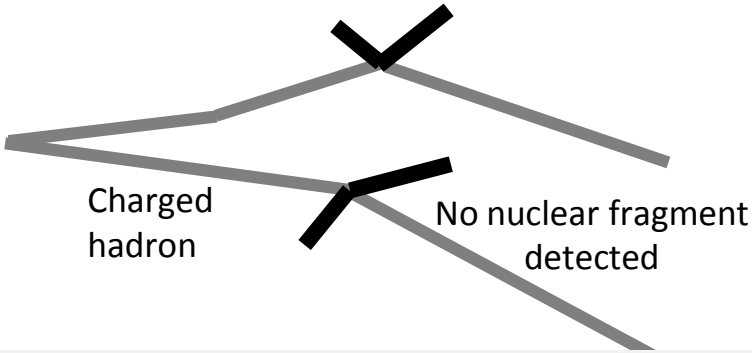


Figure 2: 1 B meson's Tau leptonic day

Signal and background rates



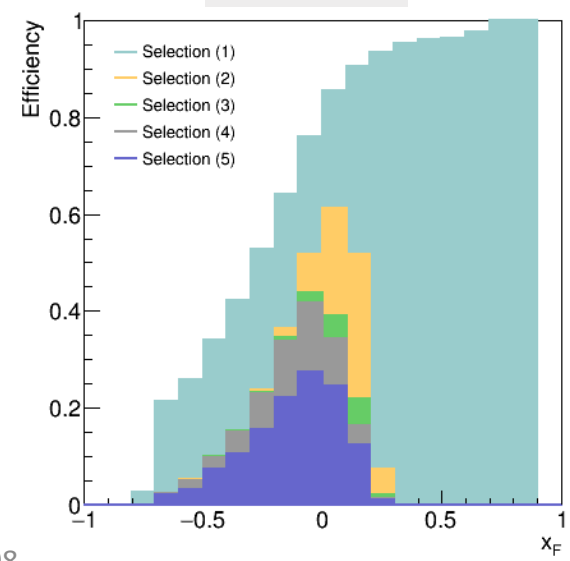
- **Signal**: Ds → τ → X events (double-kink + another decay topology within a few mm)
- Signal rate: 2.2×10^{-5} /proton int. x eff. 20%
- To detect 1000 Ds → τ → X events, 2.3×10^{8} proton interactions (4.6×10^{9} pot) are needed

- **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**

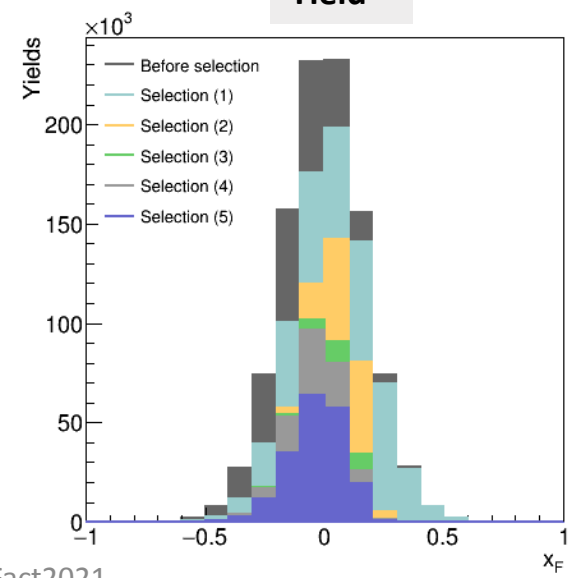
Efficiency of Ds → τ → X detection

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

Efficiency

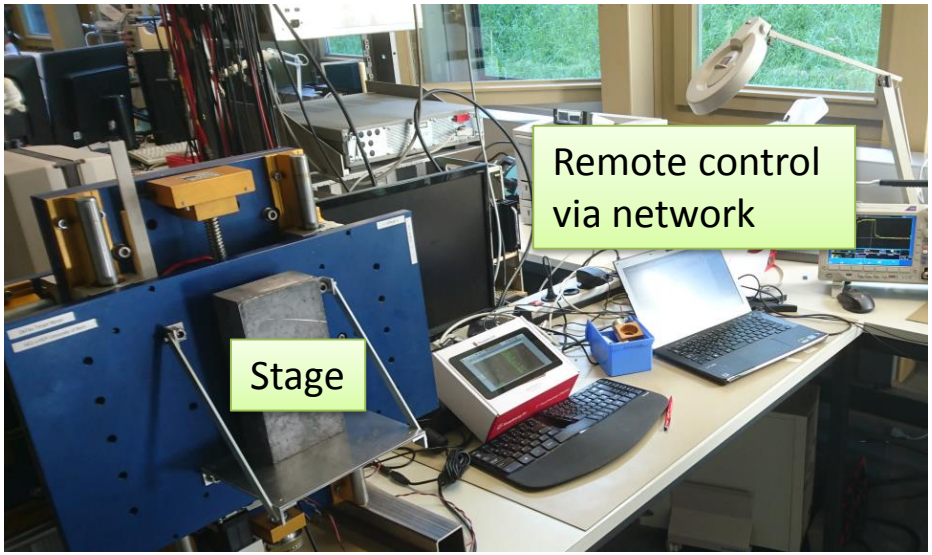


Yield

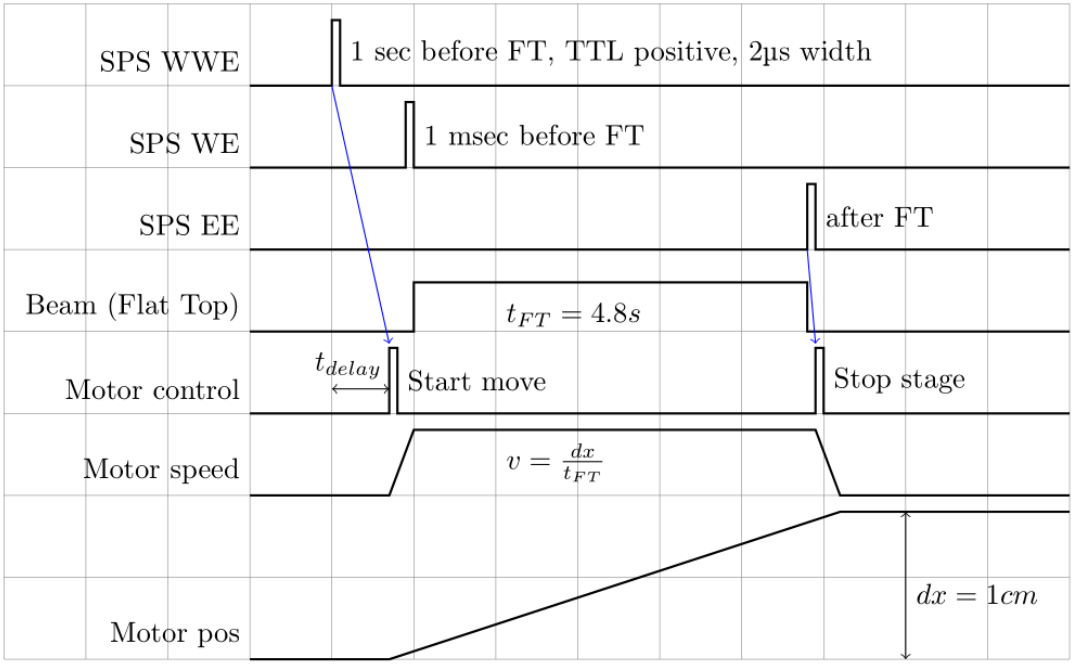


Target mover: XY stage and control

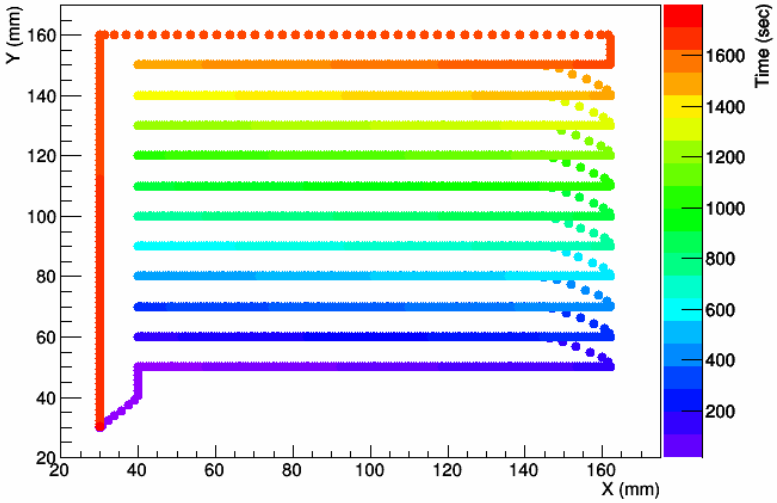
Move the modules w.r.t. the beam for uniform irradiation with a density of $10^5/cm^2$



Timing chart

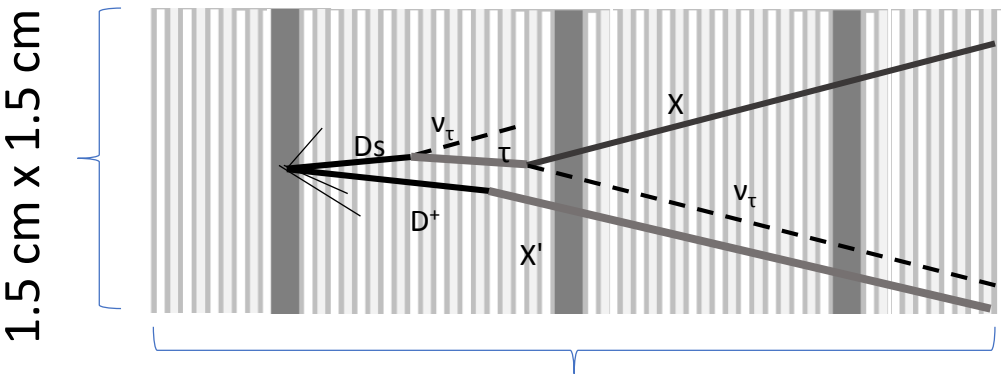


Moving test

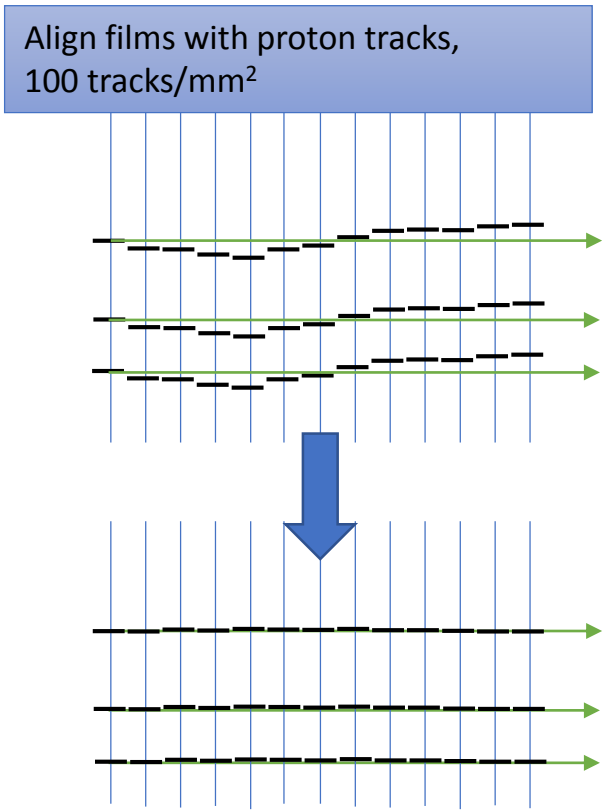


Realizing Ideal Alignment :: with plenty of 400GeV/c protons

- **High beam proton track density** ~ 10^5 /cm2
- 400 GeV/c proton :: ~**No MCS scattering** !
- 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**

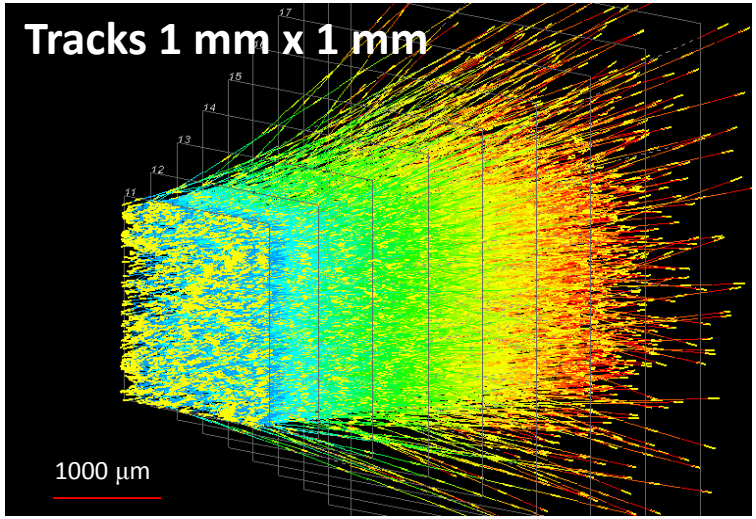


30 films
(two tungsten plates to reject low momentum daughter candidates)

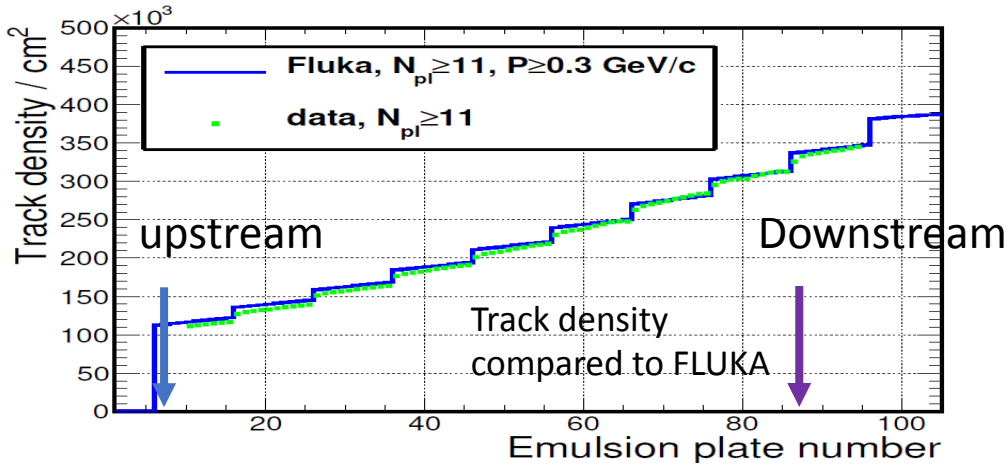


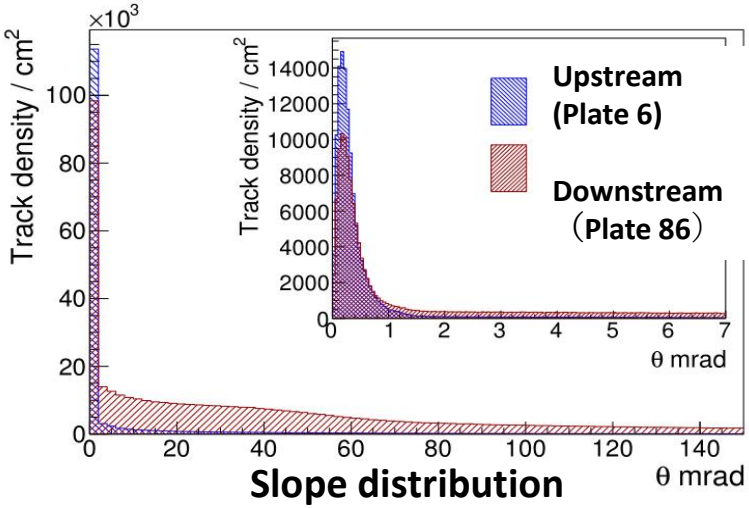
Residual of track segments to fitted line (RMS) $\simeq$**0.4 μm**

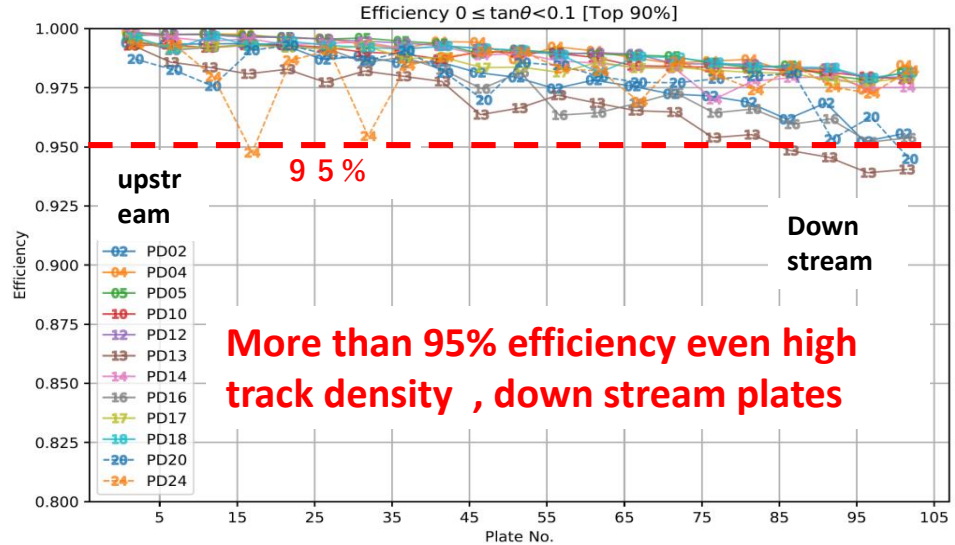
Track reconstruction, track density(Data/MC), tracking efficiency



Track density increase toward downstream due to interaction products . The MC reproduce the behavior .

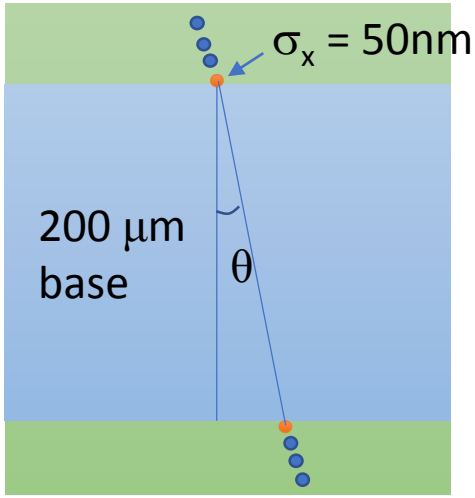


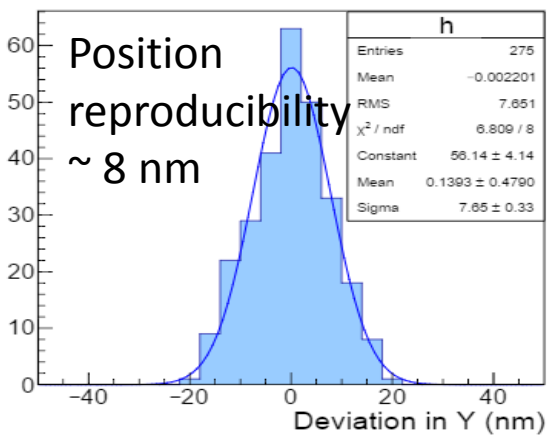


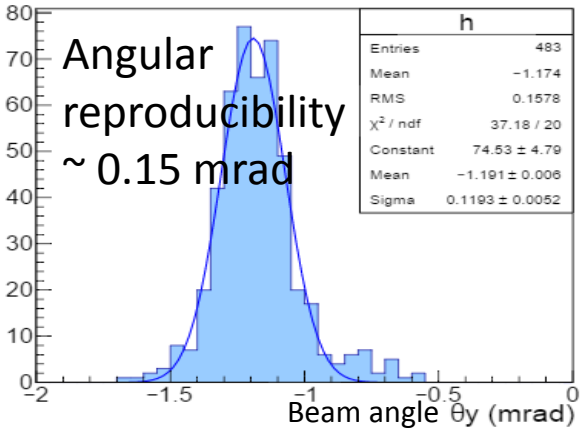


High precision measurement of track angles

- 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





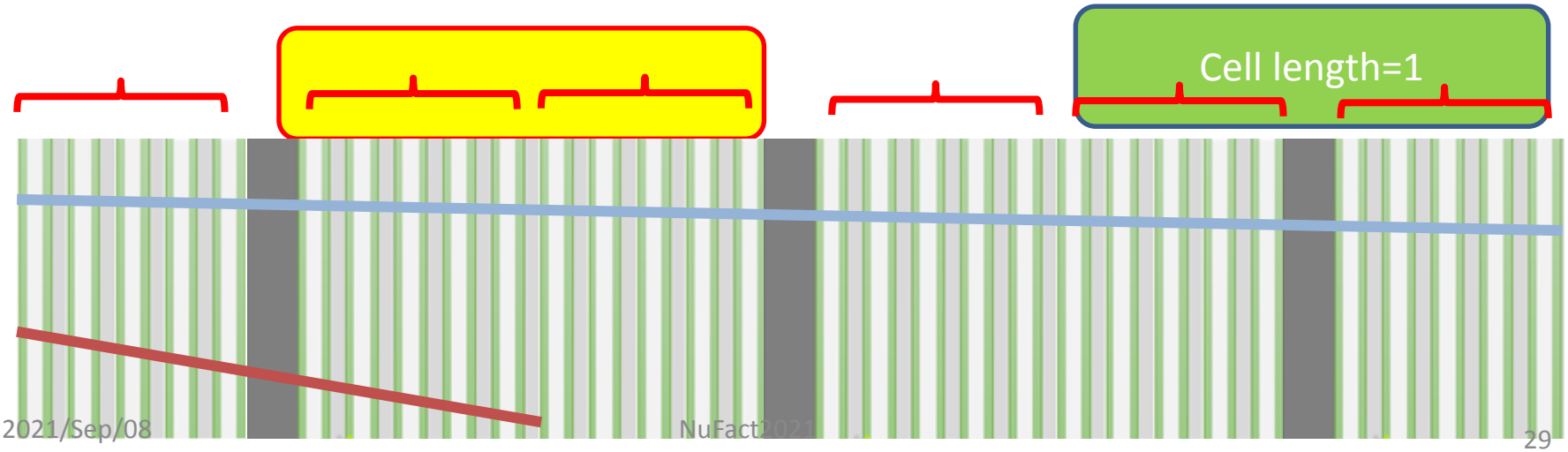


- Angular alignment between films to be done by using dense 400 GeV proton tracks

Momentum measurement

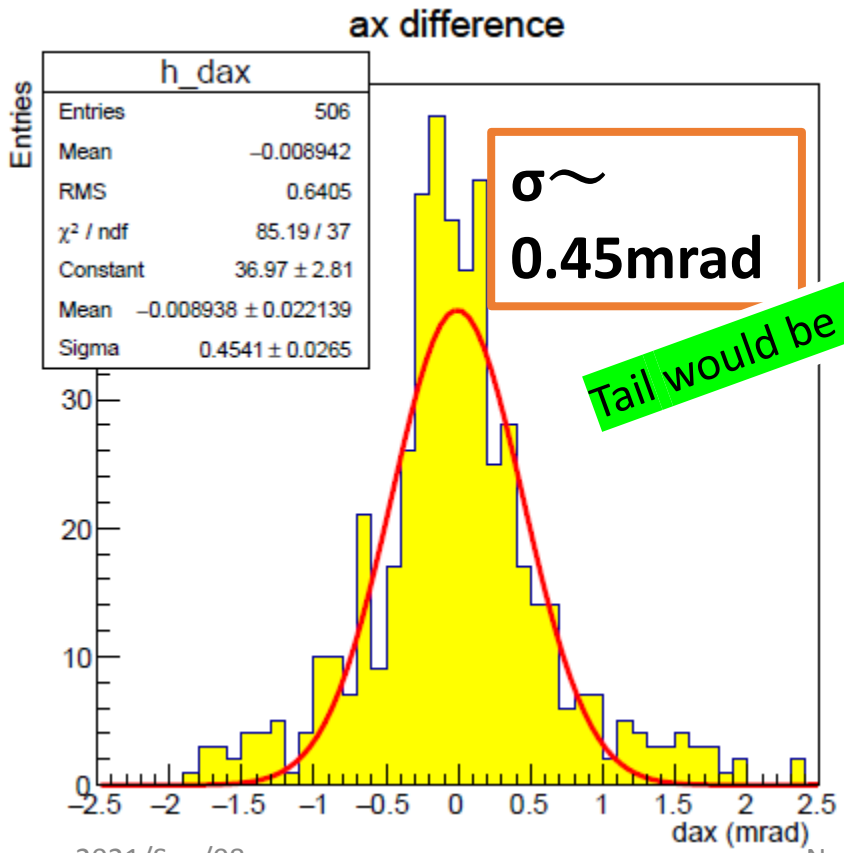
- Using 5 plates , an angle (AX,AY) was calculated .
  1. Averaged angle by 5 plates .
  2. Angle formed by position connected by first and last segment .
- Then angle difference before i-th tungsten and after j-th tungsten was calculated and take RMS for sample (j-i) cell length .
- For zero cell length conjunction angle not crossing tungsten plate are used .
- Momentum yet estimated but looking RMS vs. Cell length in next slides .

(Comment the estimated momentum by eye 1GeV/c / (rms(1Cell) / 5mrad))

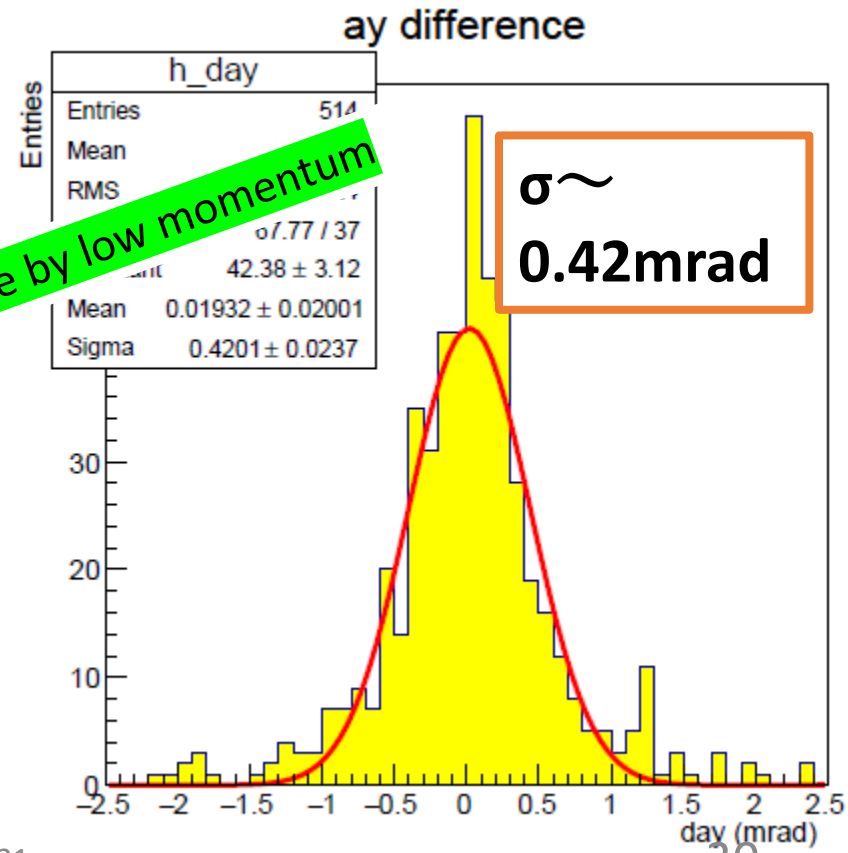


Angular difference of continuous two angles at Cell length=0 : Accuracy of the measurement

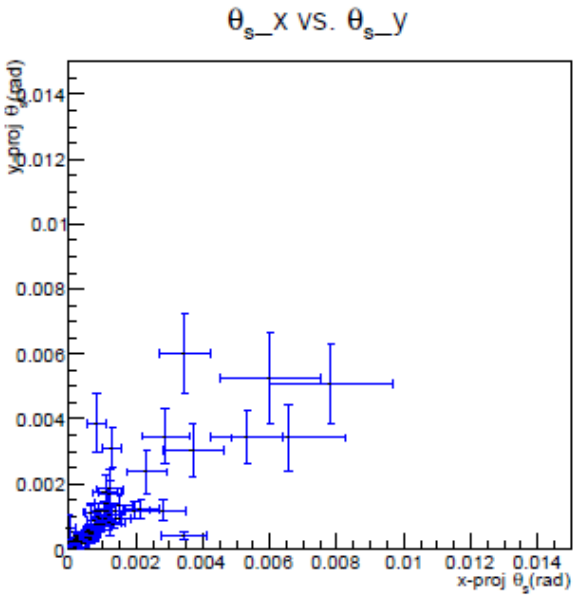
- Angle made by : 3D positions of Pl#(n) and pl#(n+4)
- Lever arm Length dZ~2mm , **Corresponds to "base" thickness 2mm**

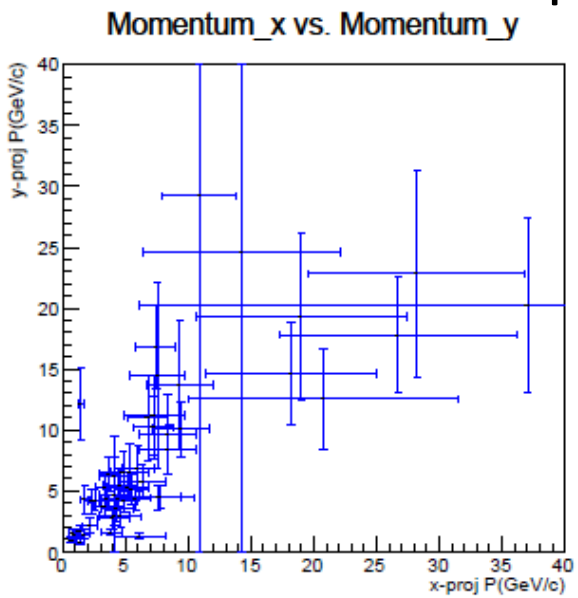


Tail would be made by low momentum

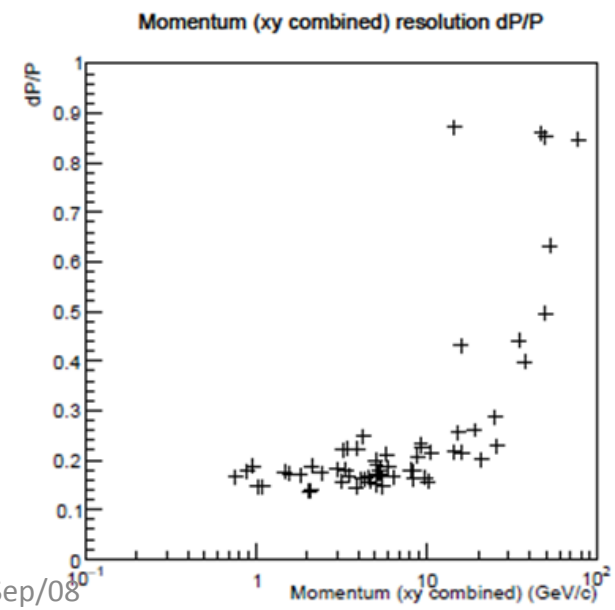


MCS Momentum measurement quality





Momentum by X and Y make linear correlation Up to ~30 GeV/c



Momentum resolution dP/P ~15-25% up to 30GeV/c