Tau neutrino study in SHiP and DsTau

5th March 2025

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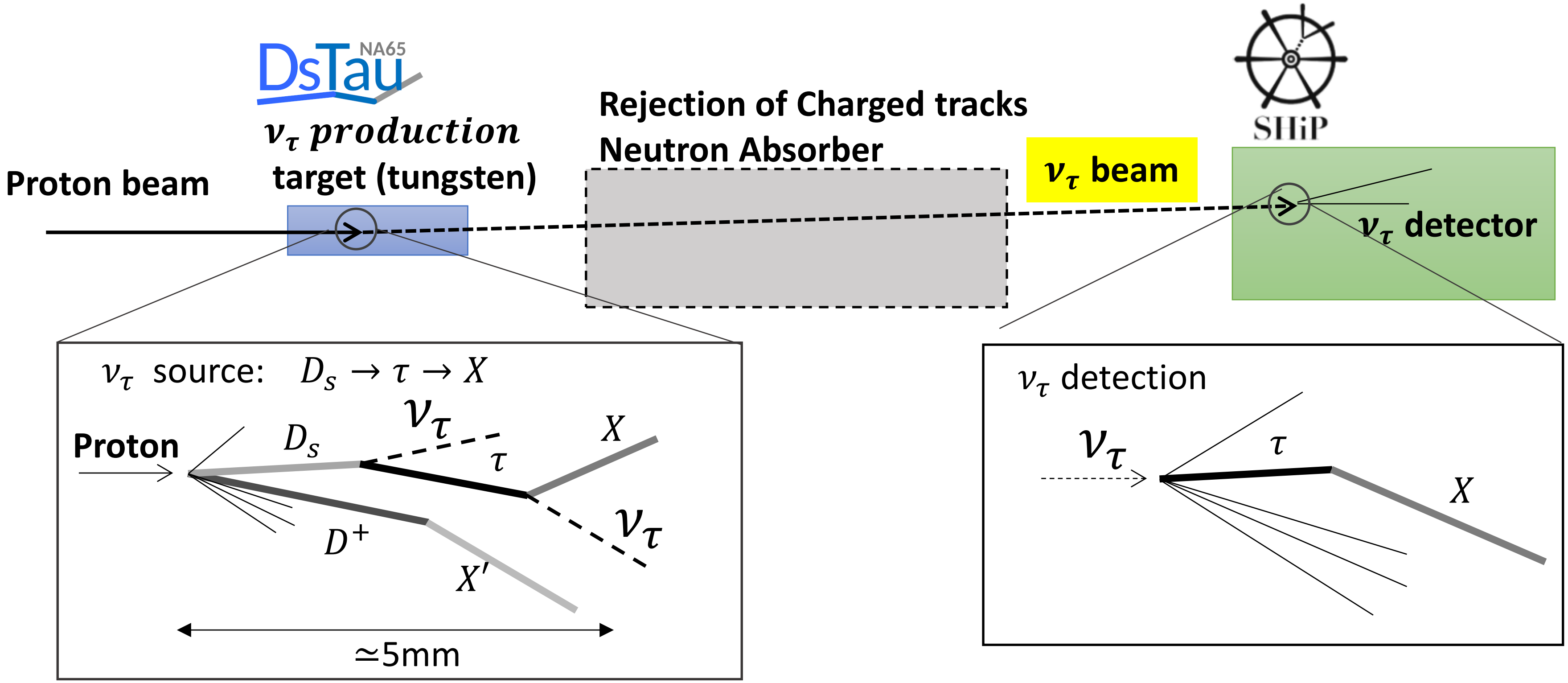
Concept of tau neutrino experiment -cross section (etc.) measurement -



ν_τ production study: DsTau

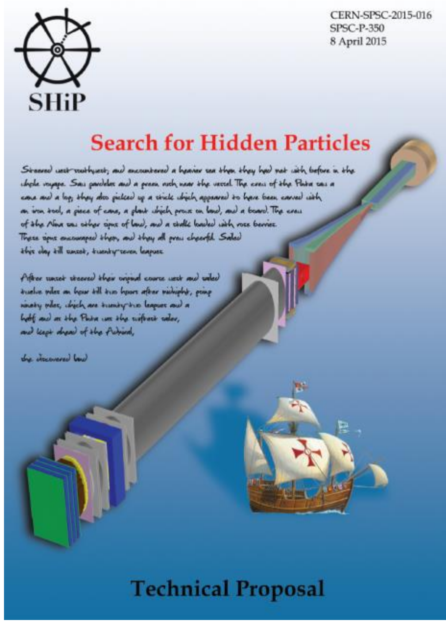
- **No data of Ds differential production cross-section**
- **Larger ~50% uncertainty of ν_τ flux**

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 ~ **50,000** events
  a few % statistical error

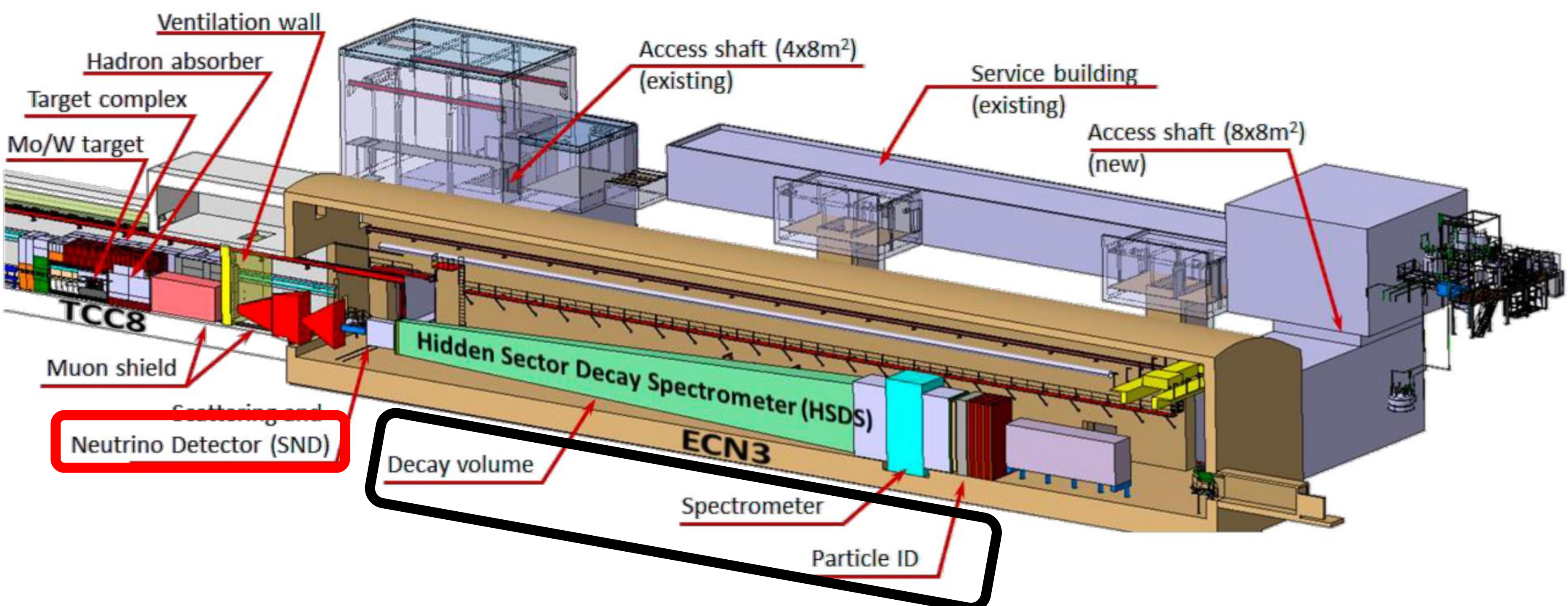
Brief history of the SHiP experiment

- **SHiP** is approved on March 2024 for intensity-frontier experiment aiming to **S**earch for **Hi**dden **P**article with mass up to *O*(10) GeV and small couplings down to 10^{-10}.
- Original proposal was submitted on April 2015
  - New beam line and experimental hall(ENC4).
  - ESPP outcome on June 2020 was unfavorable.
- Refined proposal was submitted on 2023
  - Use existing experimental hall ENC3 @North area
  - Competition between Kaon rare decay program
  - On **March 2024**, research board choose **SHiP**



170 physicist , 45 groups, 14 countries

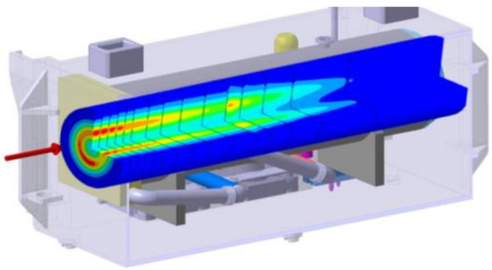
SHiP detector

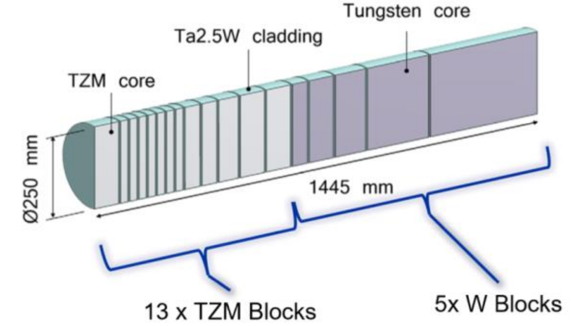


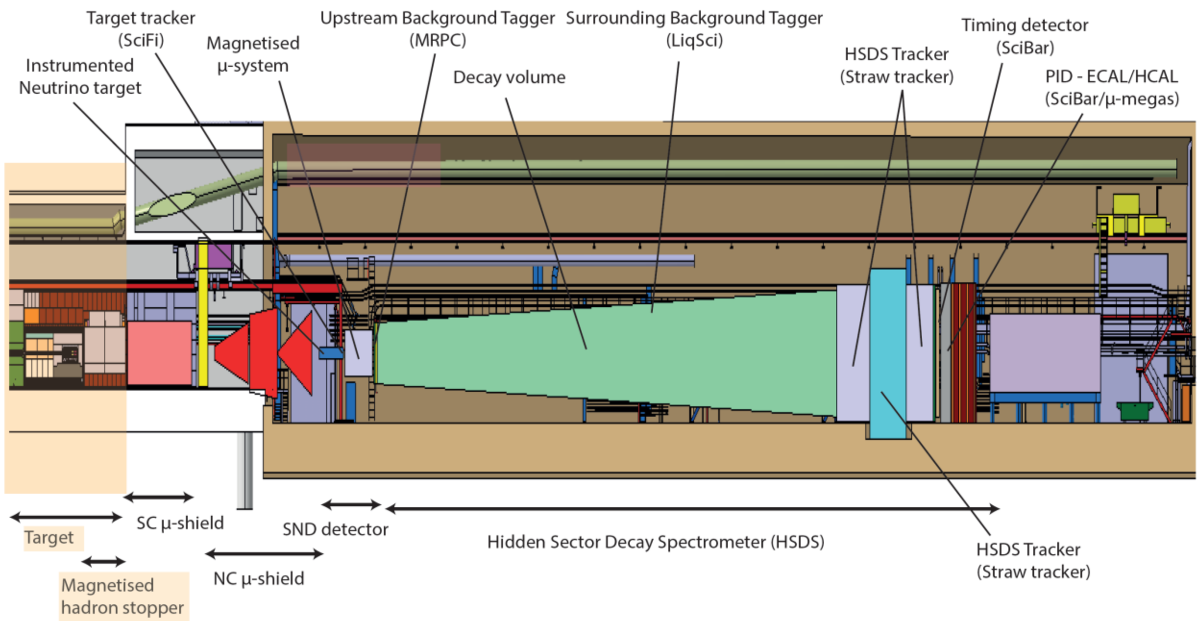
- Beam Dump Facility(BDF): **Target** and **Muon Shield**
- Two main SHiP detectors
  - **HSDS**(**H**idden **S**ector **D**ecay **S**pectrometer)
  - **SND**(**S**cattering and **N**eutrino **D**etector)

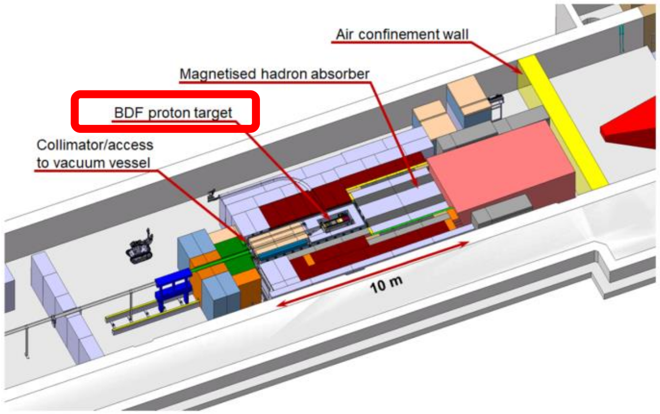
Target and Hadron stopper

- **Thick target**: 12 interaction length
- **Tough**: Mo(TZM)/W combination
- **High density**: stop light mesons before decay
- **4x10^{19} PoT/year** (Equivalent with **CNGS**)
  - ~2x10^{17} charmed hadrons **(> 10 times the yield at HL-LHC)**
  - ~2x10^{12} beauty hadrons
  - ~2x10^{15} tau leptons
  - O(10^{20}) photons above 100MeV



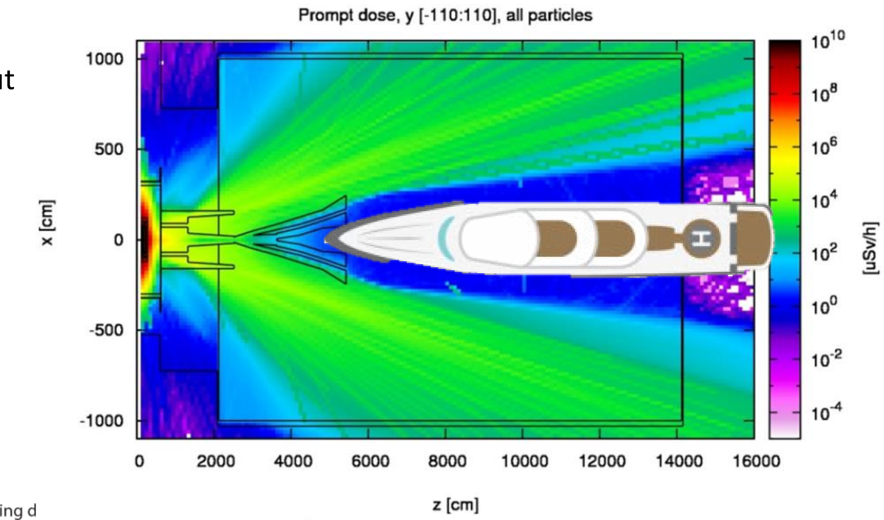


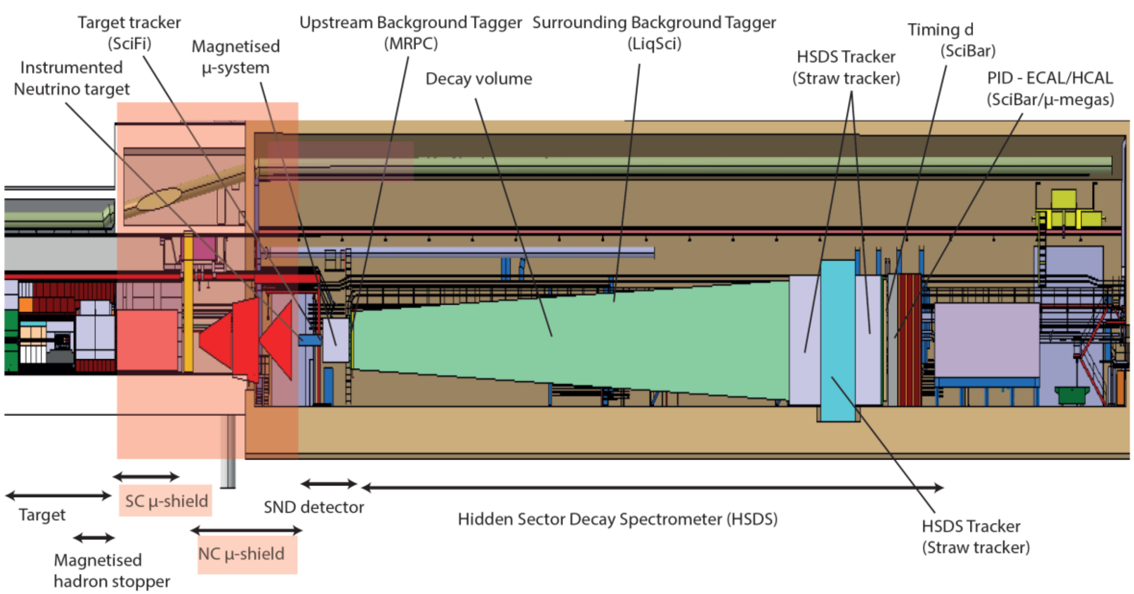


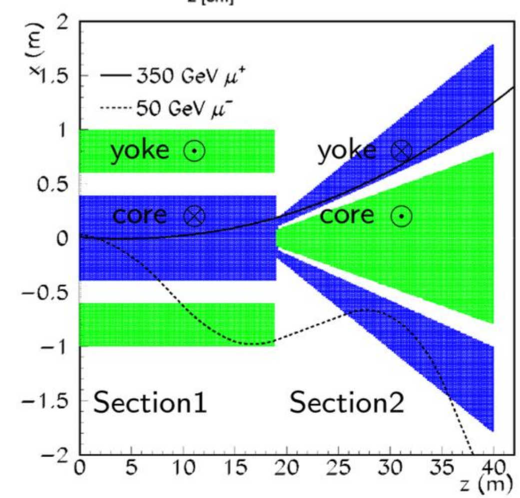


Magnetic Muon Shield

- The Muon Shield utilizes an **alternate-polarity scheme** to sweep out positive and negative muon to left and right of the detector
  - **Learned from DONUT second muon sweeper**
- **ECN3 optimization (Hybrid SC / NC)** : **5.1T**
  - Keep detector length as same as ECN4 design
- Aiming to reduce muon rate: $2\text{x}10^{10} \rightarrow <10^{5}$ per spill
- **@SND location: < 1 muon /cm^2 /spill**

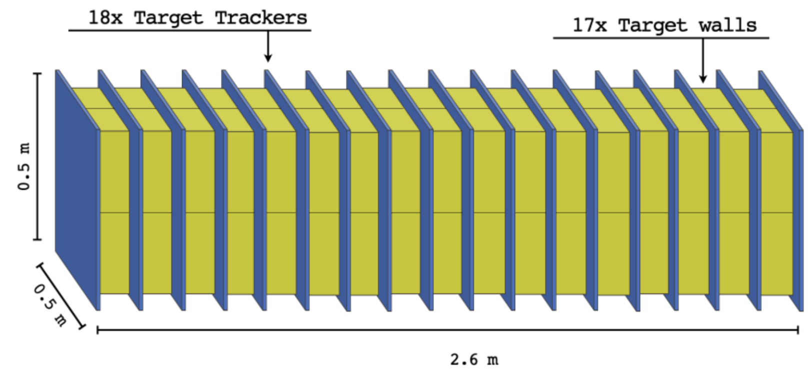


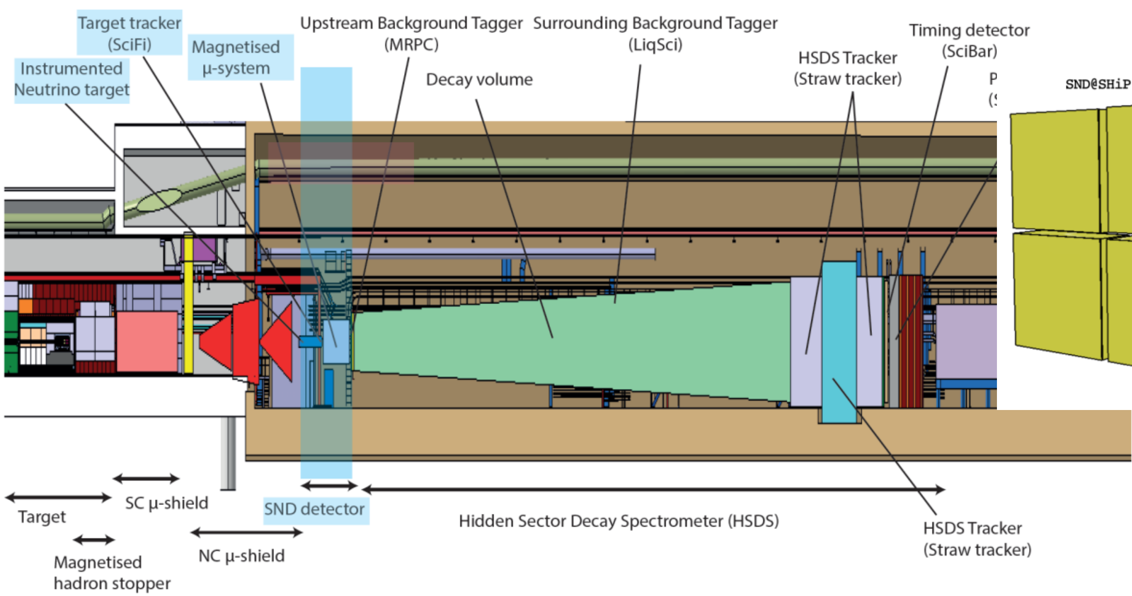


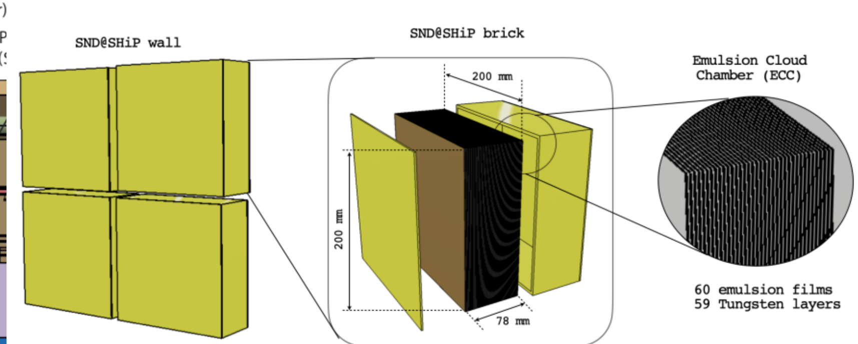


Scattering & Neutrino Detector (SND)

- **Emulsion Cloud Chamber (ECC)**
  - 1mm thick tungsten target as same as SND@LHC
- Similar with **DONUT, OPERA** and **SND@LHC**
- **17** Target walls consisting four ECC bricks each interleaved with 18 SciFi Target Tracker(TT)
  - **160 m²** for full target
- **3 tons** of target mass
- Equipped with muon spectrometer



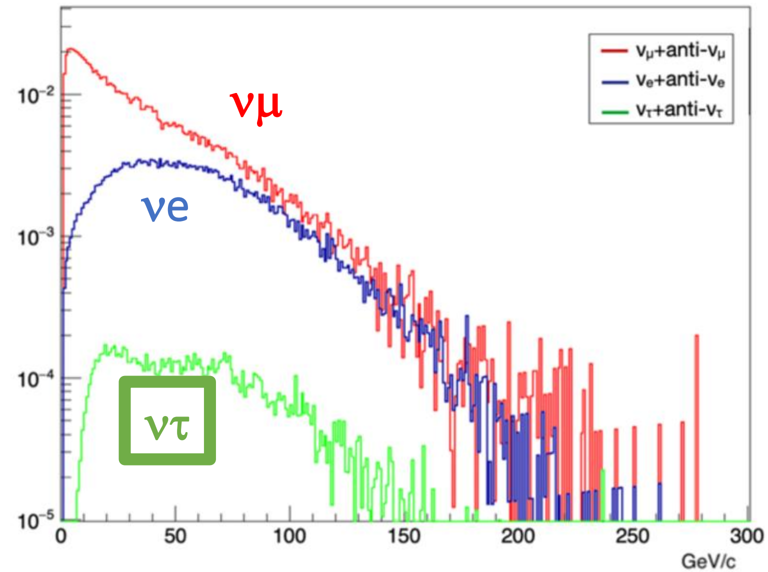




Neutrino interactions in the target

	<E> [GeV]	beam dump	<E> [GeV]	SND target acceptance	<E> [GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	30	1.3×10^{16}	63	2.8×10^{6}
N_{ν_μ}	2.6	5.4×10^{18}	8.4	1.5×10^{17}	40	8.0×10^{6}
N_{ν_τ}	9.0	2.6×10^{16}	22	1.0×10^{15}	54	8.8×10^{4}
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	22	9.3×10^{15}	49	5.9×10^{5}
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	6.8	1.2×10^{17}	33	1.8×10^{6}
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	32	1.0×10^{15}	74	6.1×10^{4}

For 6 x 10^{20} pot



53,000 detected tau neutrinos are expected

Expected ν_τ including eff. (~35%)

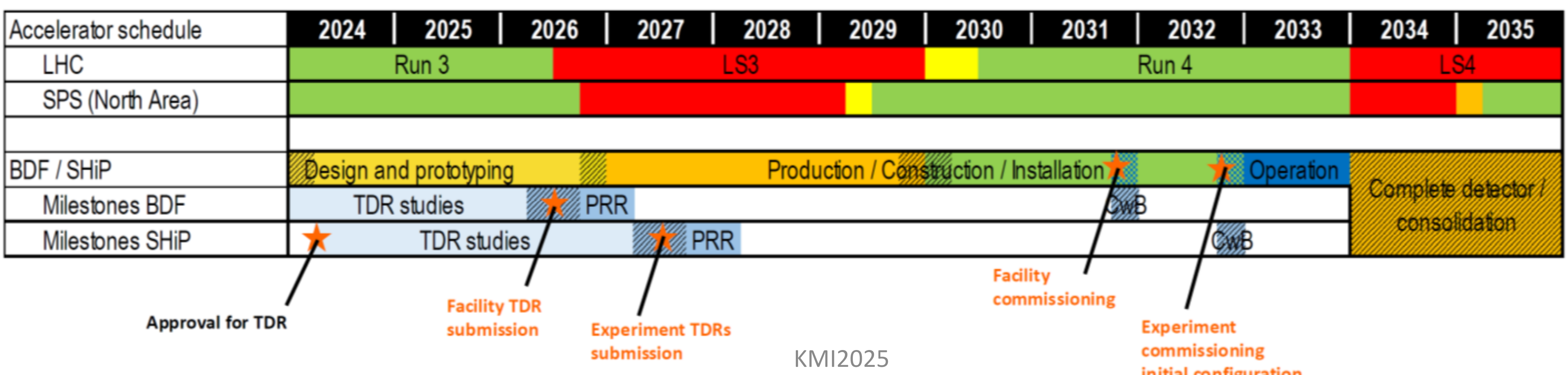
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

Statistical error < 2% for tau
Neutrino flux prediction can be <10% by NA65
(DsTau experiment expect 1000 Ds to tau decay)

Best neutrino beam for Lepton Universality study
All three neutrino flavours from same charm decay
1~3% in ratio

SHiP Summary

- **SHiP** approved, March 2024,
  intensity-frontier experiment aiming to **S**earch for **Hi**dden **P**article
- Two main detector in SHiP
  - **H**idden **S**ector **D**ecay **S**pectrometer (**HSDS**)
  - **S**cattering and **N**eutrino **D**etector (**SND**)
    - Using Emulsion Cloud Chamber(**ECC**) as same as **DONUT** and **OPERA**
    - The best tau neutrino beam is produced in the **B**eam **D**ump **F**acility (**BDF**)
- Realistic prototype experiment running at LHC neutrino beam
  - SND@LHC and FASERν using ECC
- In this three years of TDR phase, detector optimization is on going.
- SHiP will be operational in **2032**



DsTau Experiment (CERN NA65) motivation

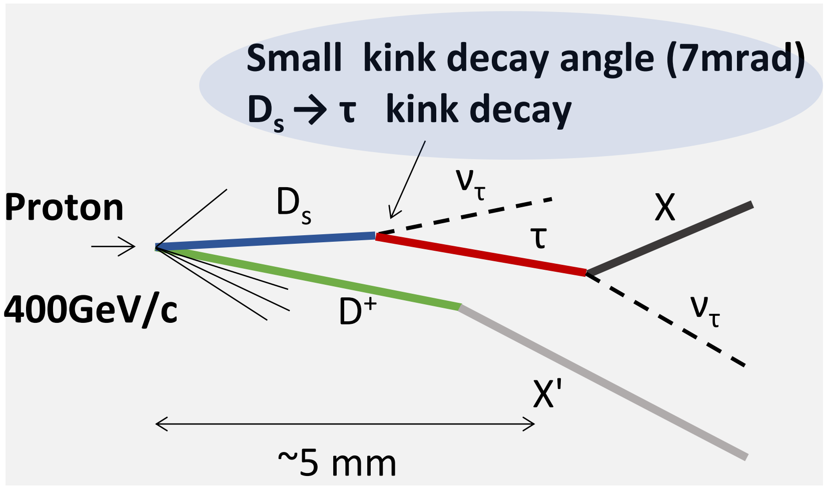
Precise understanding of ν_τ production flux

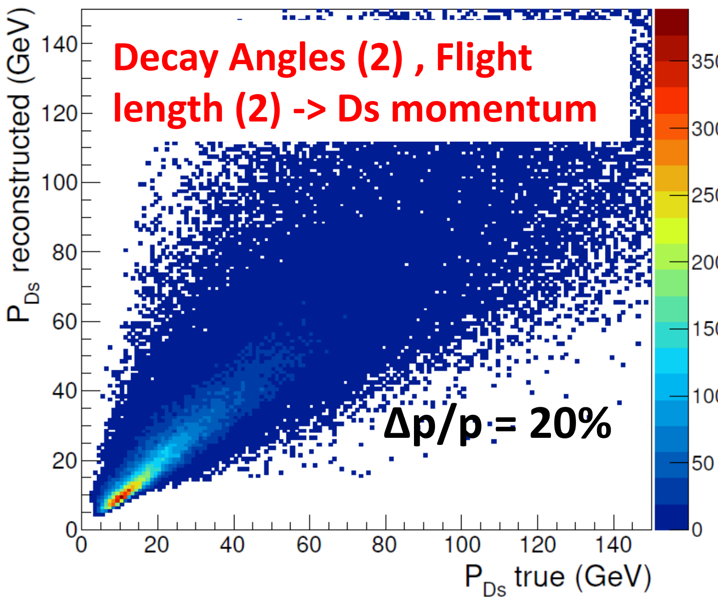
Measurement of **differential production cross section of Ds** .
Using a specific decay topology :: Ds->tau->X (double kink) decay .

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

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) main physic targets

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 nt program etc .

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

Several **10^5 events having pair charms!** among int. produced tracks.

sub-micron spatial resolution of Nuclear Emulsion detector allow us study also ..

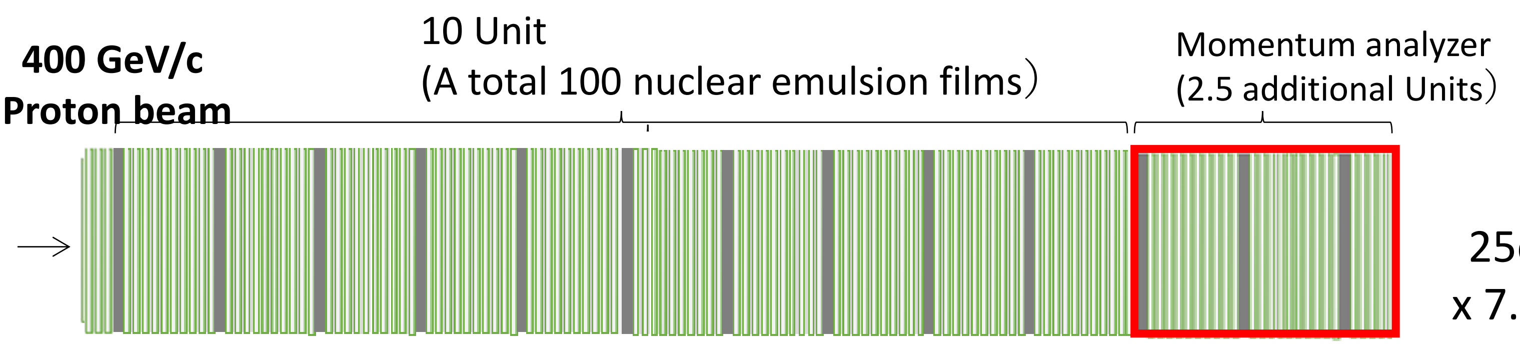
2. Understanding of charm production

The correlation of the charm pairs , angle (slope , phi) , momentum by ~10^5 events
X_F distribution for Charged and Neutral charm respectively.
Wide acceptance and sub micron spatial resolution of
Analysis about Charms produce into Forward direction :: intrinsic charms exist ? .

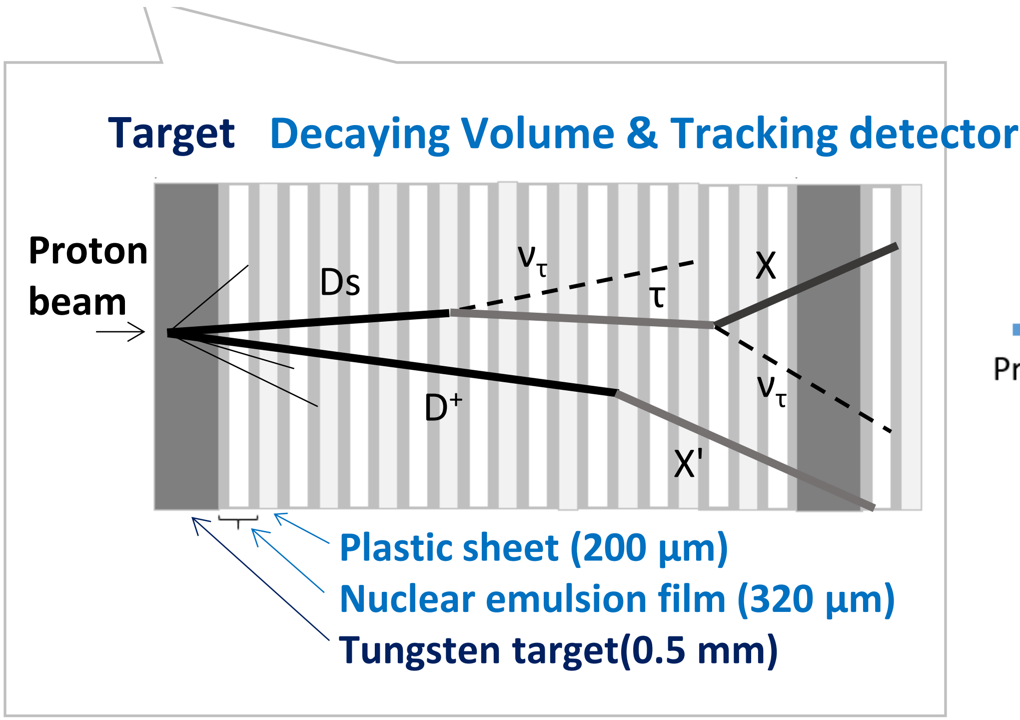
The detector structure (~80 modules)

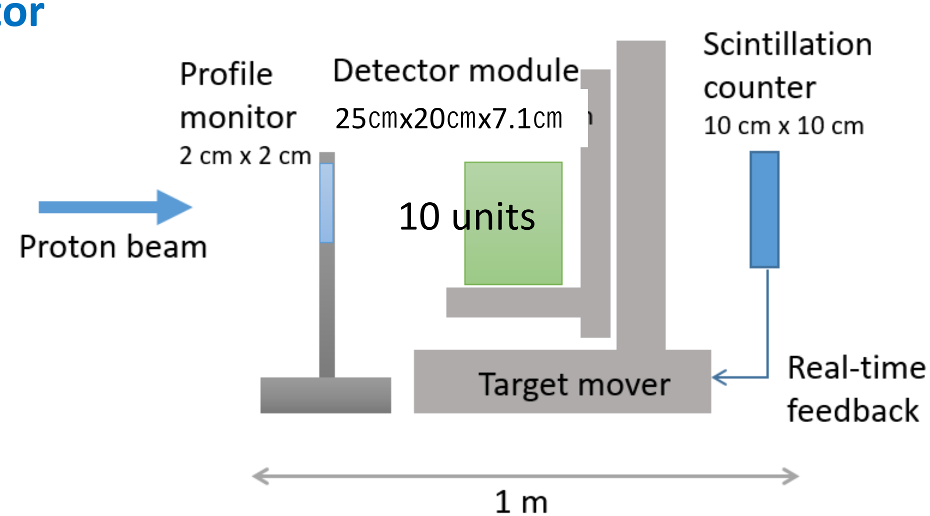
NA65 DsTau

2.3x10^{8} Proton-tungsten interactions (4.6x10^{9} POT)



ECC size
25cm x 20 cm
x 7.1cm (beam)





Uniform irradiation on detector surface x,y

Accumulated proton on ECC modules

NA65 DsTau

	Modules (Physics run size)	Total surface area of used emulsion (m^2)	Integrated # of ECC modules	Interactions with tungsten/molybdenum Integrated ($\times 10^8$)
Pilot run 2018	¼ x 30 = 7.5	49	7.5	0.19
Physics run 2021	**17**	**110**	**24.5**	**0.61**
Physics run 2022	**17**	**110**	**41.5**	**1.04**
Physics run 2023	**40**	**260**	**81.5**	**2.04**

※Emulsion films are produced at Nagoya University

SHiP approved in March 2024
A hybrid beam dump target**, Molybdenum alloy** ($_{42}$Mo: above 99% purity)+ **tungsten($_{74}$W).**
DsTau have taken data with both metals.

Run	All	# of Molybdenum ECC module	# of Tungsten ECC module
2021	17	5	12
2022	17	8	9
2023	40	20	20
Total	74	33	41

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 m^2/h/面

Angle resolution ~2 mrad

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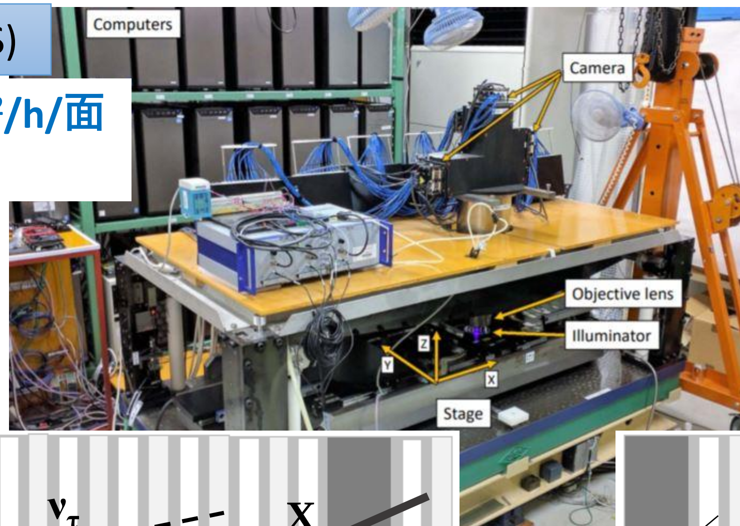
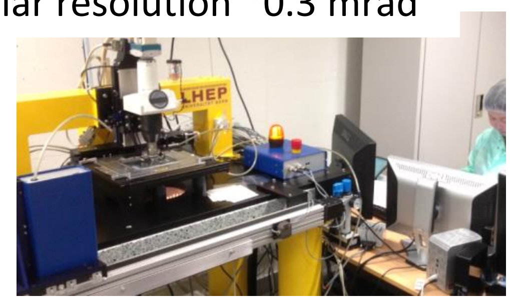
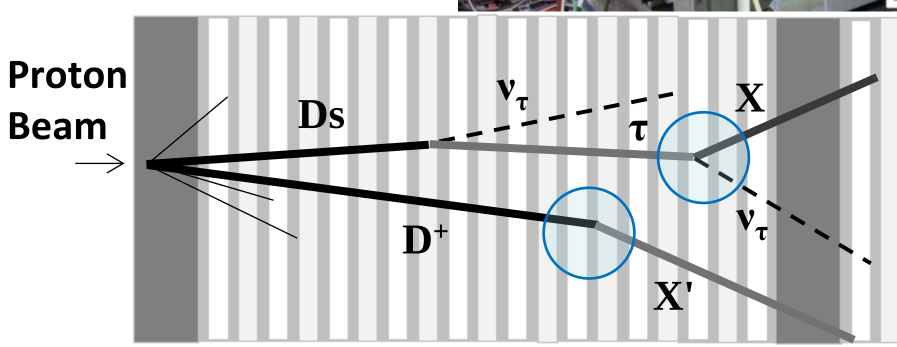
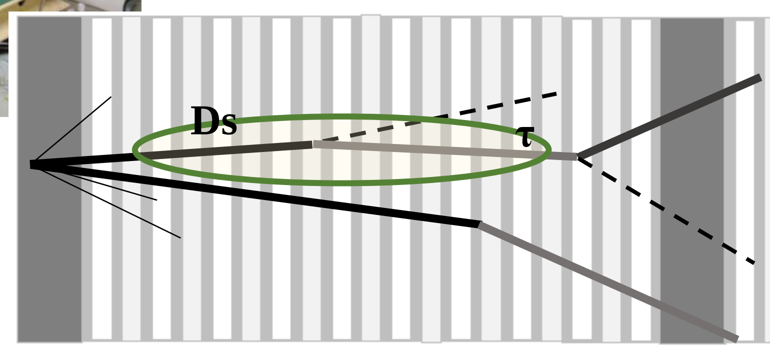


Dedicated microscopes

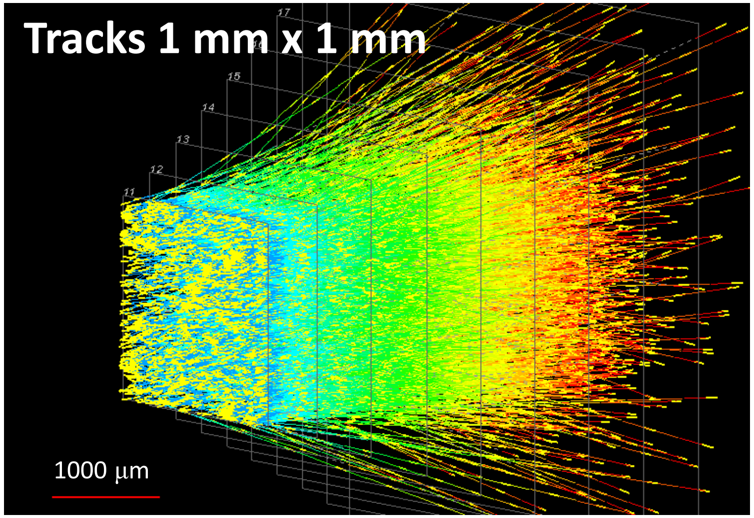
Angular resolution ~0.3 mrad



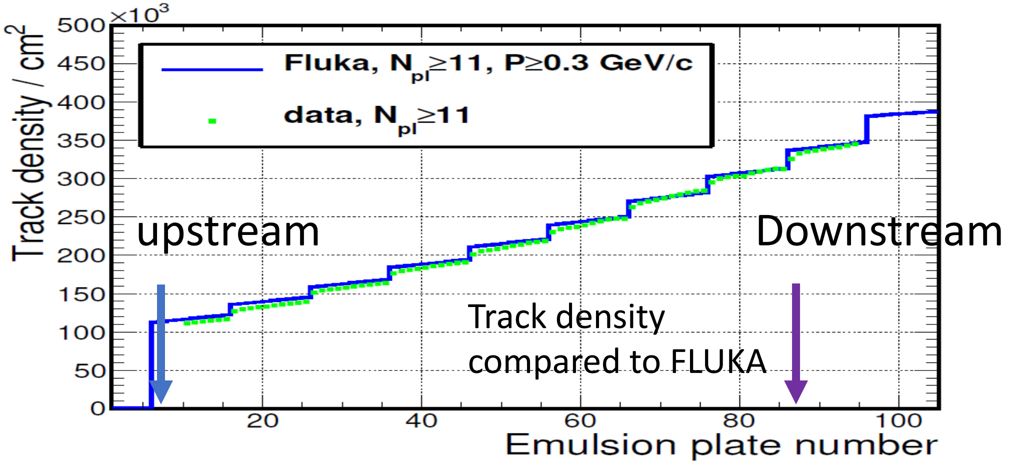


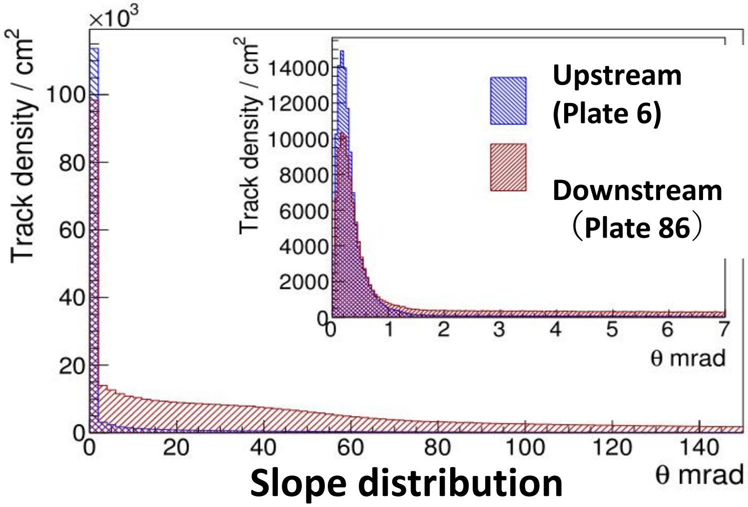


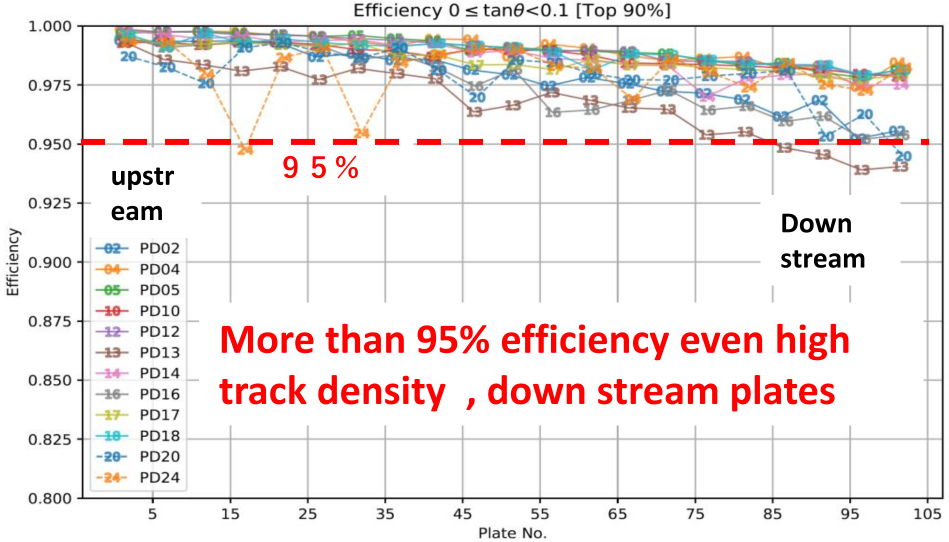
Track reconstruction, track density(Data/MC), tracking efficiency



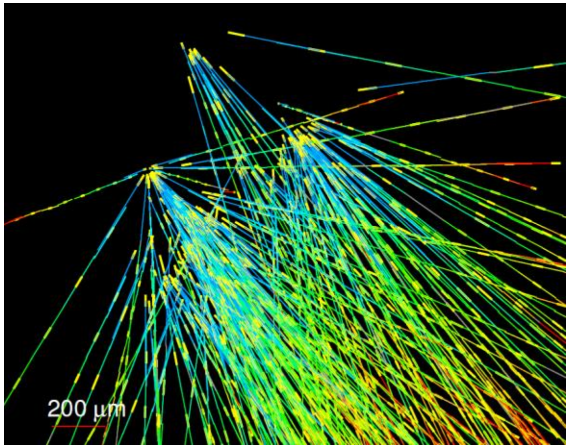
Track density increase toward downstream due to interaction products . The MC reproduce the behavior .



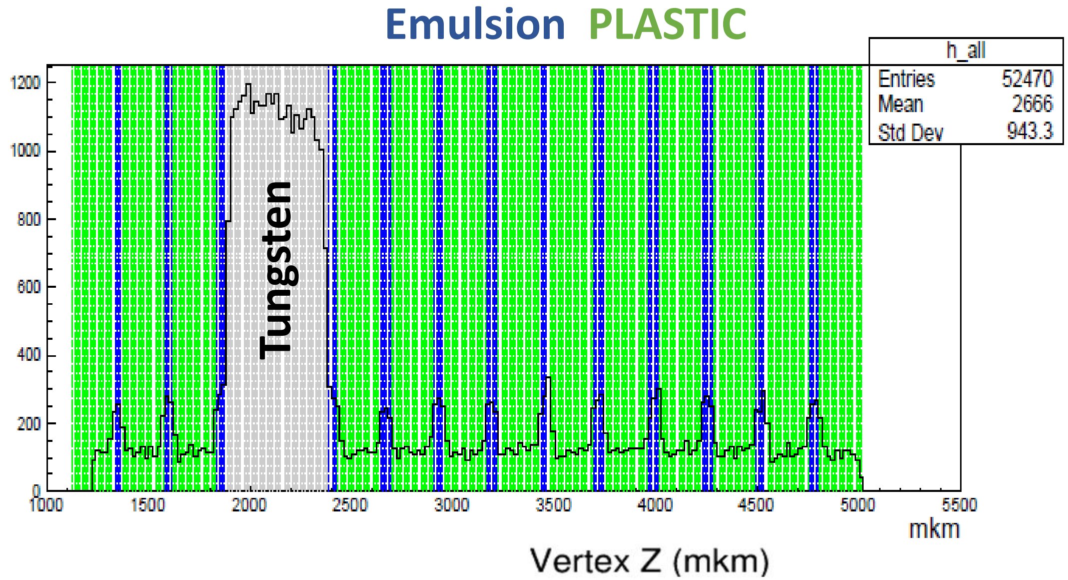


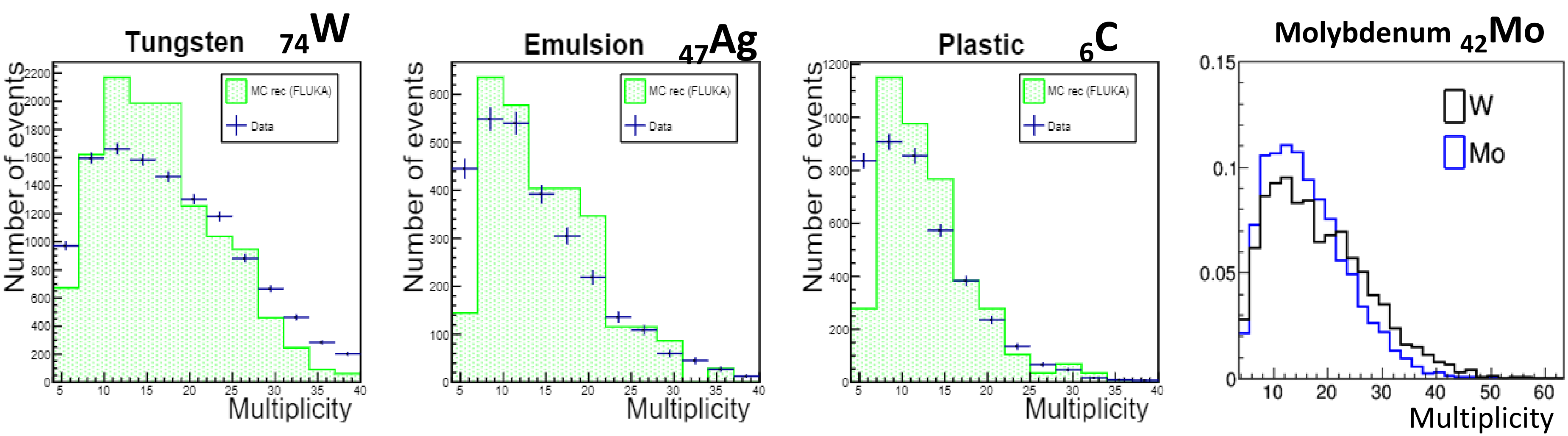


Proton-target nucleus interaction



Interaction density par a tungsten plate~500/cm





Multiplicity distribution for composed material interactions.

Analysis of proton-tungsten interactions

A sample of about 95,000 proton-tungsten interactions are analyzed in detail.

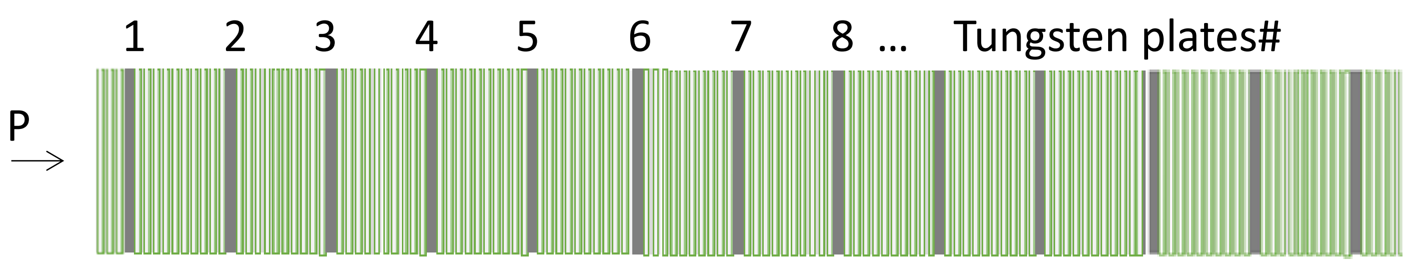
Paper appear soon : accepted by EPJC, arXiv:2411.05452v1

Multiplicity and **angular distributions** and Proton-Tungsten interaction length are discussed in.

Tungsten Plate	N	N_0	$\frac{N}{N_0}$ (%)
1	13,586	3,310,658	0.41
2	13,390	3,292,677	0.41
3	12,653	3,256,746	0.39
4	12,256	3,214,141	0.38
5	11,745	3,157,020	0.37
6	11,264	3,082,105	0.36
7	10,645	2,996,099	0.35
8	9,775	2,892,348	0.34
Total	95,314	25,201,794	0.38

Proton-tungsten interaction length

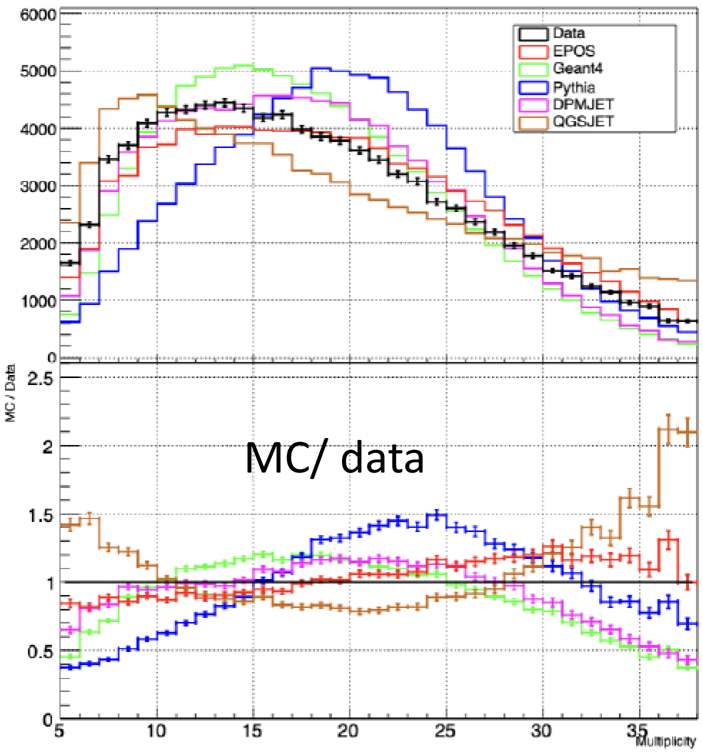
Sub-volume	Data(mm)	EPOS(mm)
1	91.0 ± 2.5	95.2 ± 2.7
2	90.8 ± 2.5	95.5 ± 2.8
3	93.7 ± 2.6	95.3 ± 2.8
4	93.9 ± 2.7	95.5 ± 2.8
5	94.5 ± 2.7	94.8 ± 2.8
6	94.4 ± 2.7	95.0 ± 2.8
7	94.7 ± 2.8	98.1 ± 3.1
8	96.8 ± 3.0	97.0 ± 3.1
Mean	93.7 ± 2.6	95.8 ± 2.8



Multiplicity and Angular distribution of proton- tungsten interaction.

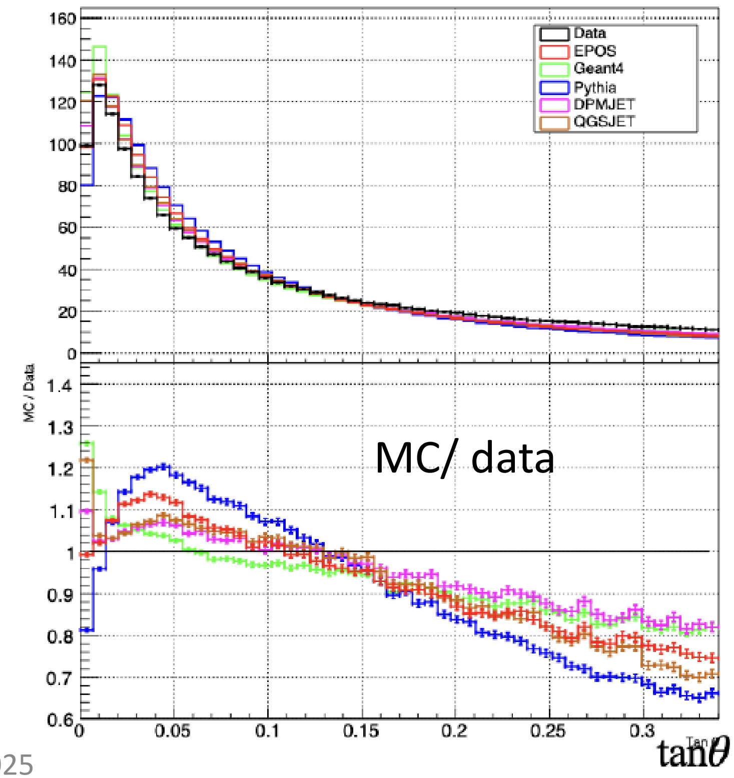
- Compared with several MC generators
- Some discrepancy between data and MC.
- EPOS looks the best among the test MC generators
- 10-20% discrepancy with EPOS

Multiplicity Distribution



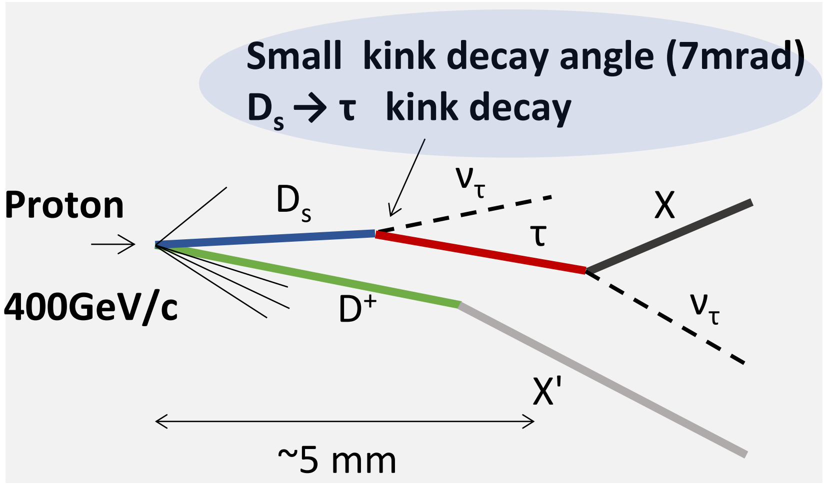
Multiplicity (# of tracks / interaction)

Anglular Distribution



Ds→tau→X search

- A total of ~1.9 x 10^6 p-tungsten interactions of pilot run data is analyzing.

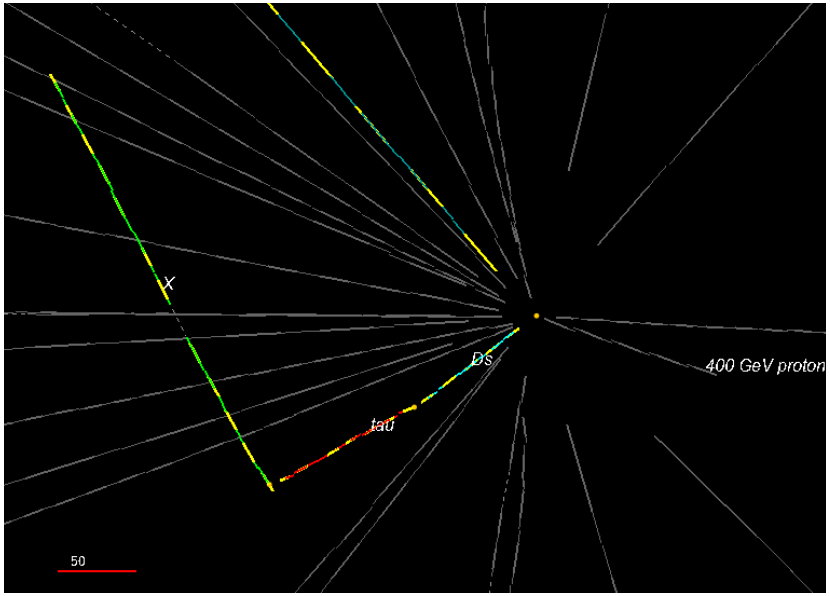


- A preliminary selection applied to the sample to enrich the Ds→tau→X signals.
- Daughter X and X' momentum obtains from Multiple coulomb scattering.

- Several candidate event's decay geometories confirmed by Viewer and Kinematical checks.
- Analysis on going .

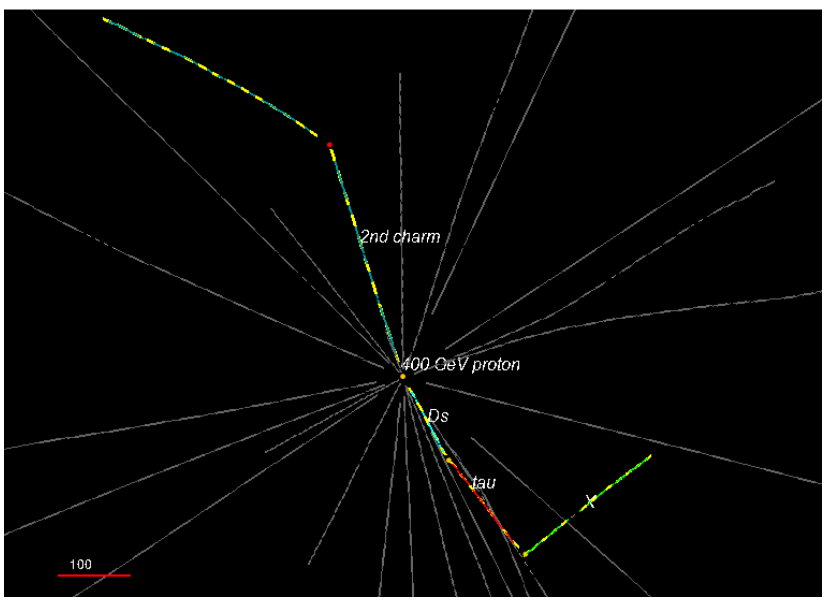
	Current status	If all this done
P-W interactions	1,863,286	1863286
Selected events	88	88
Event Viewer Check	88	88
Confirmed events	34	34
Daughters Momentum measured	16	34
Pt > 0.1 for both tau->X and partner charm	5	10.6

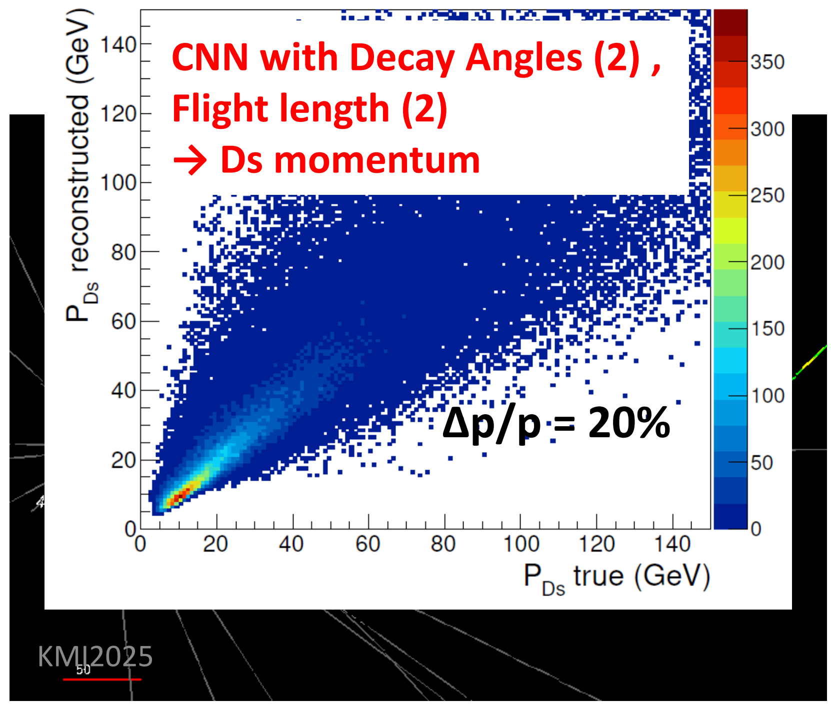
Example of a Ds→Tau→X candidate



Decay	Kink angle	Flight length
Ds→tau	8.3 mrad	2.35 mm
tau→X	28.9 mrad	4.59mm
Charm→X'	40.9 mrad	5.44mm

Ds momentum estimated as 27 GeV/c
by two decay angles and flight lengths





Summary

- The **DsTau** study **Ds → tau → X** differential production cross section by **400 GeV/c proton**- tungsten interactions.
- **Beam exposure have been successfully finished, Pilot run 2018 , Physics run 2021-2023**.
- A total of **$2x10^8$** proton-tungsten interactions were accumulated in ~80 ECC modules .
- **1000** Ds→tau→decays from the interactions to be detected.
- Reduce uncertainty on tau neutrino flux, 50% → 10% and provide for **SHiP (2032 commissioning).**
- **Ds → tau kink decay in short flight of a few mm and very small kink angle require nuclear emulsion detector.**
- **Nuclear emulsion tracker** provides ideal two track separation in **3D** and alignment accuracy **~0.4um**.

- A preliminary analysis have been conducted by 1.9×10^6 p-tungsten interactions.
- **Several candidates** shows Ds→tau→X double kink geometory and pass preliminary kinematical cuts.
- Next step is Ds differential production cross section reports.

- During the main analysis ~**10^5** Charm pair associating proton interaction will be collected .
- Properties of Charm pair production will be studied in detail . To be **Feedback to MC generators** .

  Charm particle correlation of the pairs .

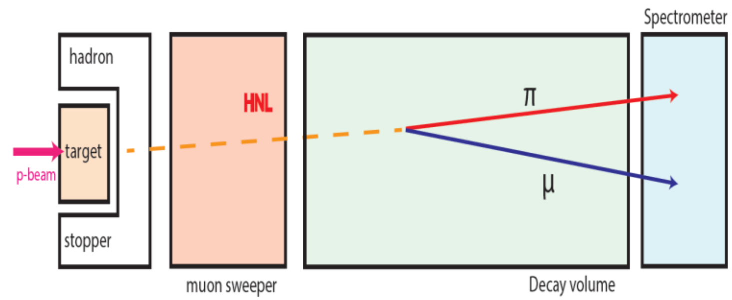
  Valence quark like charm particle**, Intrinsic Charm** production in **forward direction** test ?
- **Proton interaction with right (CH), medium (Ag,Br), heavy (W, Mo) nucleus**, properties

  Comparison with MC generators, **understanding** especially tracks produced in **Forward direction** .

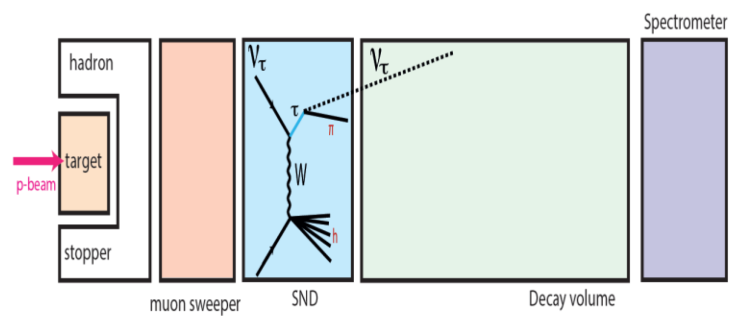
SHiP detector concepts

	Physics model	Final state
HSDS	SUSY neutralino	$\ell^\pm\pi^\mp,\ \ell^\pm K^\mp,\ \ell^\pm\rho^\mp, \ell^+\ell^-\nu$
	Dark photons	$\ell^+\ell^-, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
	ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
	HNL	$\ell^+\ell'^-\nu, \pi l, \rho l, \pi^0\nu, q\bar{q}'l$
	Axino	$\ell^+\ell^-\nu$
	ALP (photon coupling)	$\gamma\gamma$
	SUSY sgoldstino	$\gamma\gamma, \ell^+\ell^-, 2\pi, 2K$
SND	LDM	electron, proton, hadronic shower
	$\nu_\tau,\ \overline{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^\pm,\ D^\pm,\ D^0,\ \overline{D^0},\ \Lambda_c^+,\ \overline{\Lambda_c}^-$

Visible decay to SM particles



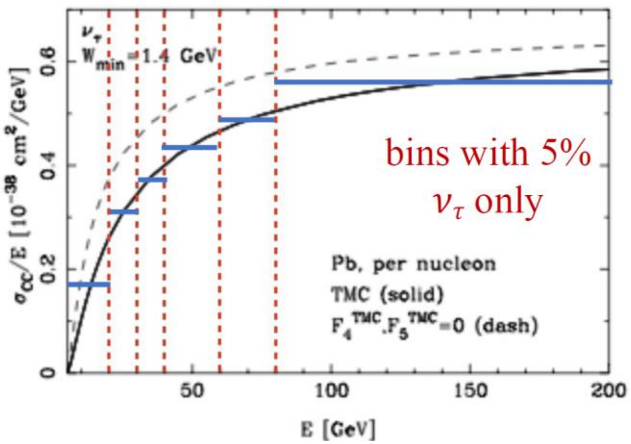
Scattering off atomic electrons and nuclei

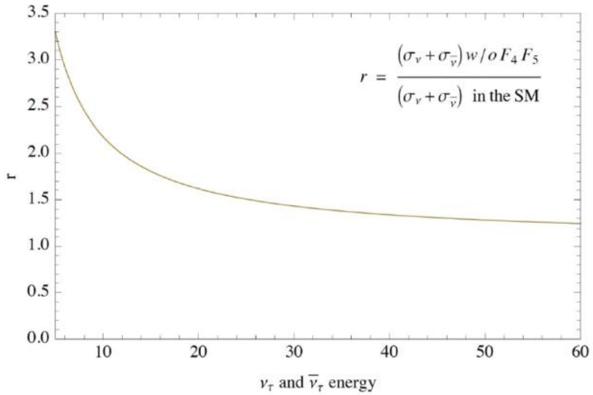


F4/F5 structure functions by ν_τ

$$\frac{d^2\sigma^{\nu(\bar\nu)}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\right),$$

- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV





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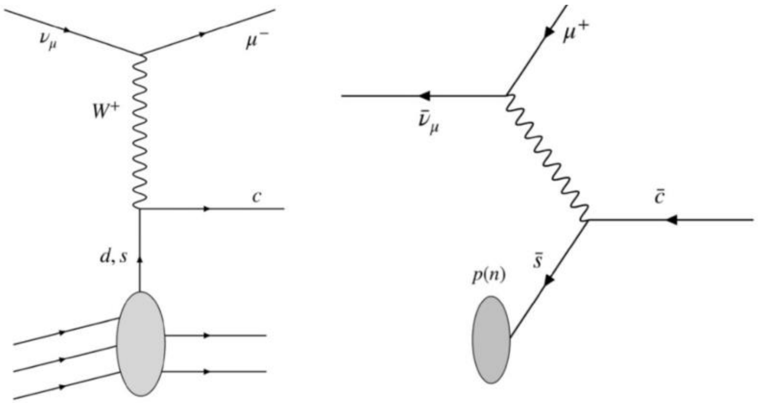
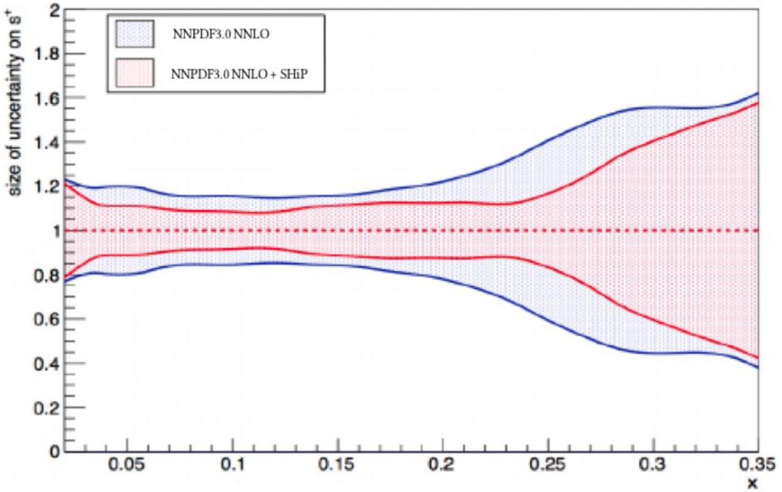
Assuming 10 equally populated bins (with 5% uncertainty) for ν_τ + anti- ν_τ
A global 20% effect on the cross-section w/wo F4 and F5

Strange quark content



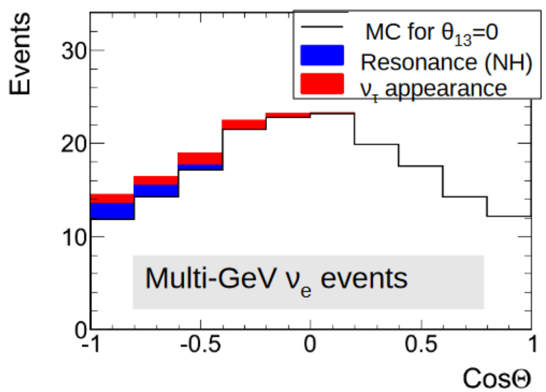


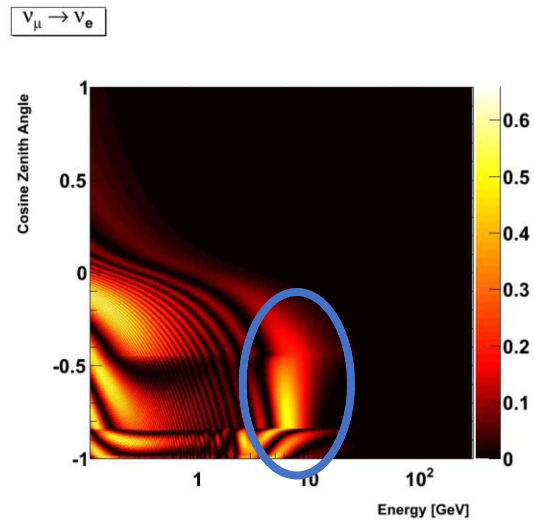
	<E> (GeV)	CC DIS with charm prod	Charm fractions (%)
N_{ν_μ}	57	3.5×10^5	4.4
N_{ν_e}	71	1.7×10^5	6.0
$N_{\overline{\nu}_\mu}$	50	0.7×10^5	3.8
$N_{\overline{\nu}_e}$	60	0.3×10^5	5.3
total		6.2×10^5	

Charm production via anti-neutrinos dominated by s-bar quarks because of $|V_{cd}/V_{cs}|^2 \sim 1/20$.

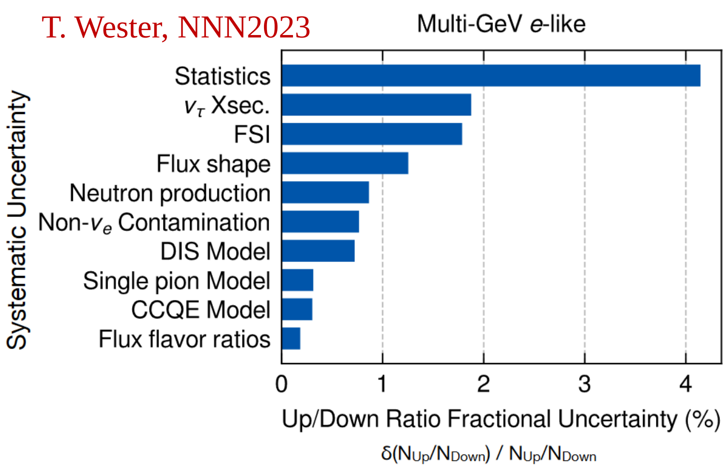
Impact of ν_τ measurements on oscillation

C. Bronner, https://indico-sk.icrr.u-tokyo.ac.jp/event/5223/





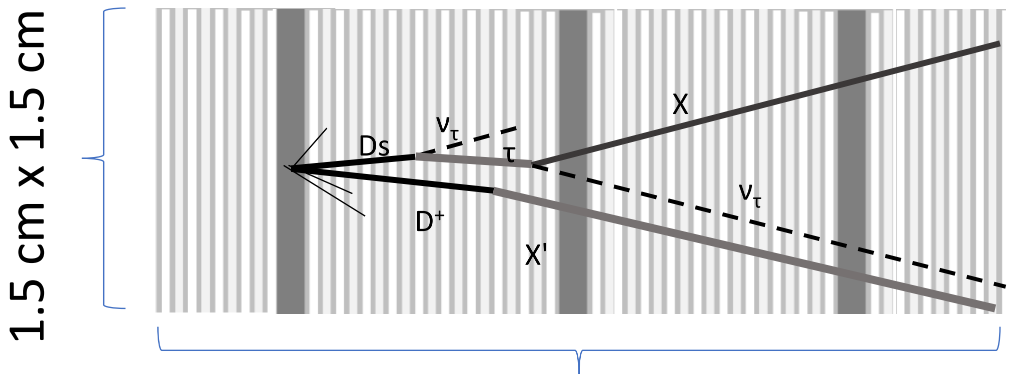
T. Wester, NNN2023



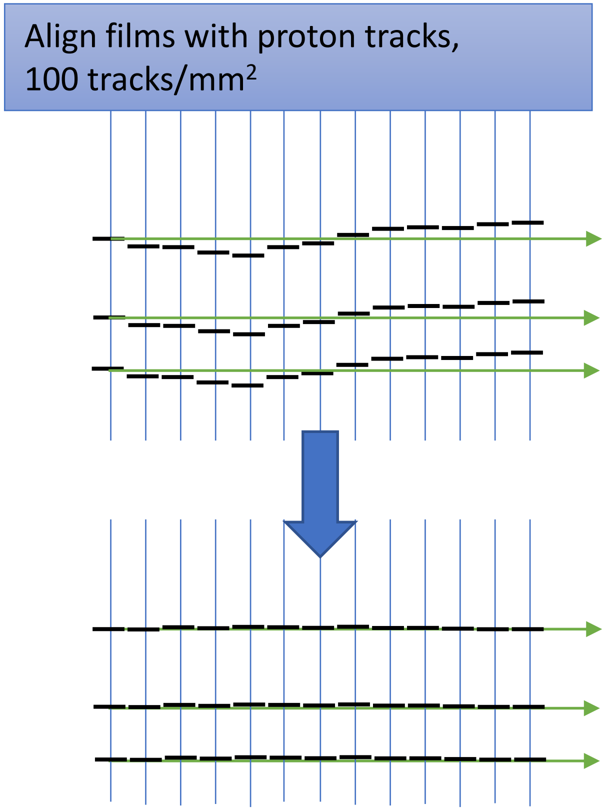
- Mass hierarchy study with atmospheric neutrino study at SK and HK
- Tau neutrino interactions with an energy of few 10 GeV mimic multi-GeV ν_e interactions

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)

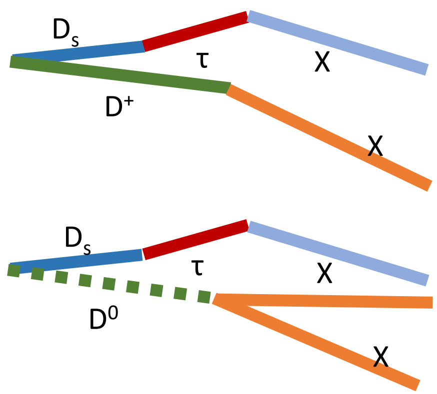


Residual of track segments to fitted line (RMS) $\simeq$**0.4 μm**

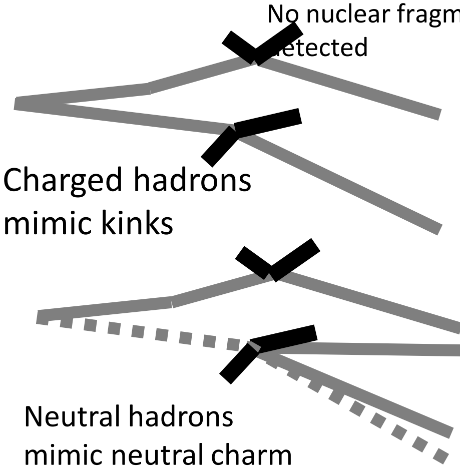
Signal and background

- Signal

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



- Main background: Hadron interactions of daughters of proton interactions



Neutral hadrons mimic neutral charm decays

Detection efficiency = 20%, estimated with Pythia 8.
Signal probability 2.2x10^{-7} /proton

Signal in DsTau : 1000

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

Tau neutrino interaction cross section

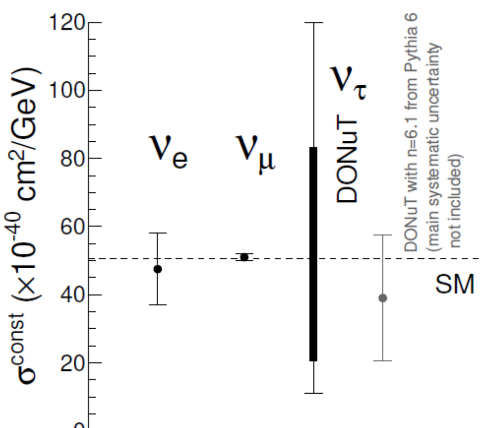
ν_τ properties are not well measured, identical with $\nu\mu$,νe ?

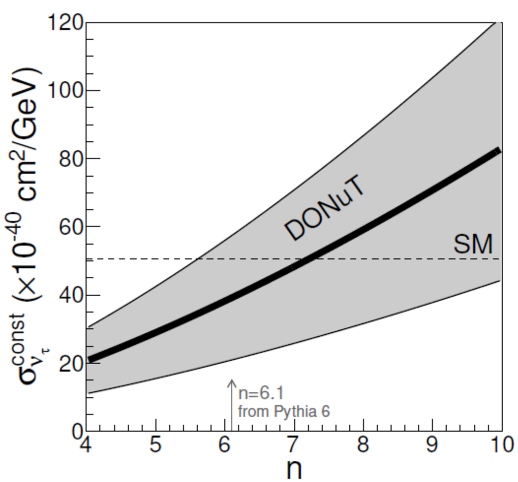
Large uncertainty on interaction cross section.

→ ν_τ interaction cross section precise measurement

New physics tests in tau neutrino interactions

Input for future neutrino oscillation studies, cosmic ν_τ observation .





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

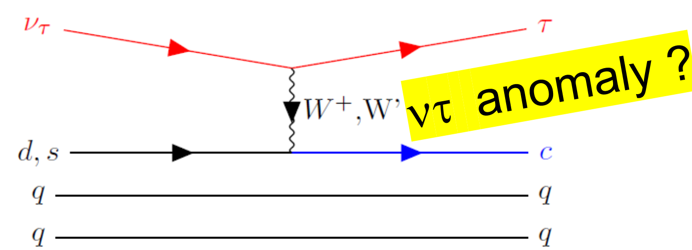


Figure 1: ν_τCC Charm 生成

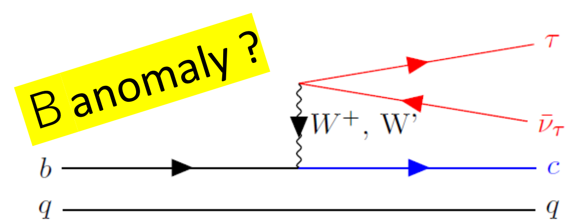
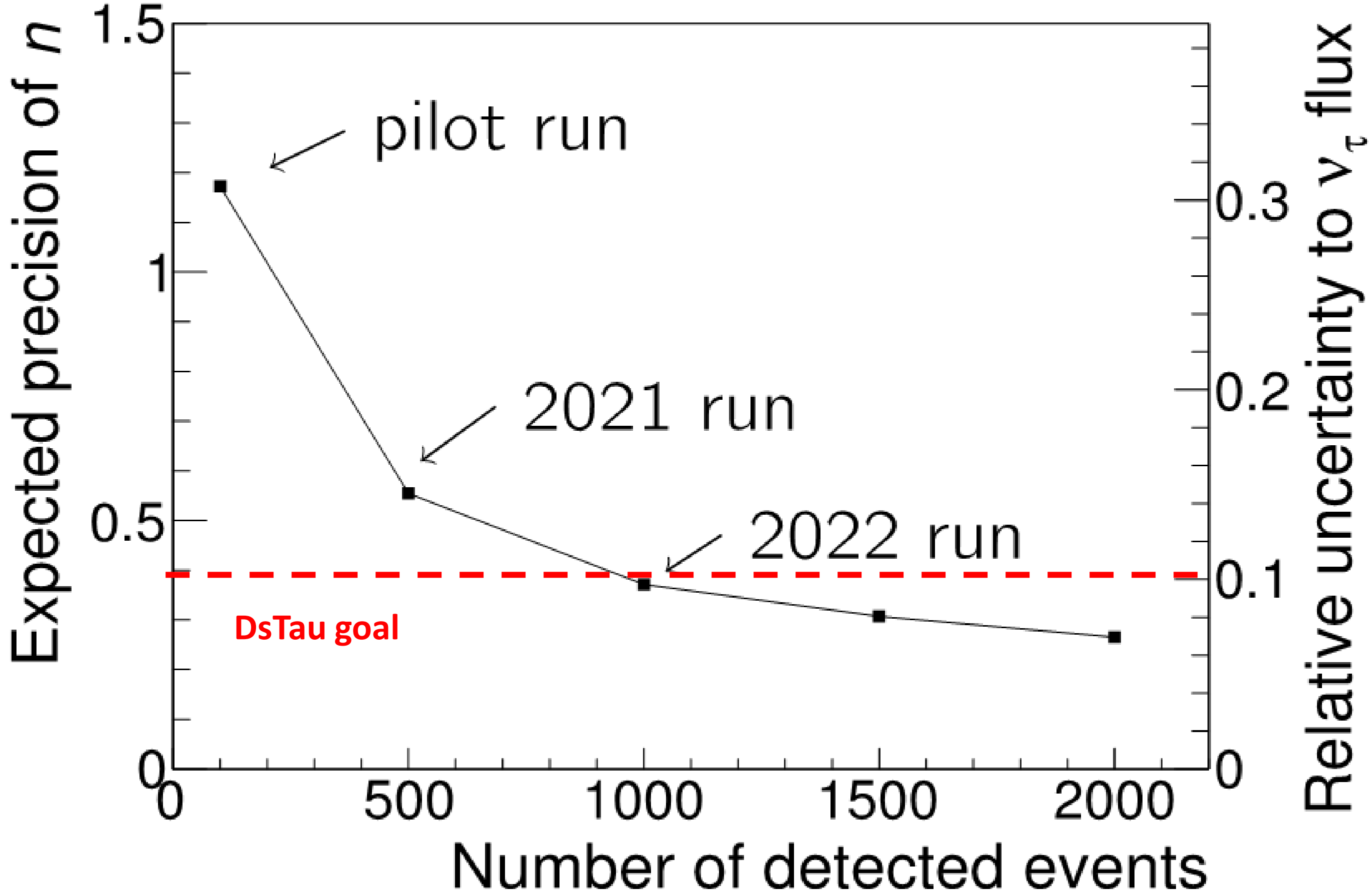


Figure 2: B 中間子のタウレプトニック崩壊

Plan for physics runs

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

30



Ds→tau→X detection efficiency and its X_F dependency

Selection	Total efficiency (%)
(1) Flight length of $D_s \geq 2$ emulsion layers	77
(2) Flight length of $\tau \geq 2$ emulsion layers and $\Delta\theta_{D_s \to \tau} \geq 2$ mrad	43
(3) Flight length of $D_s < 5$ mm and flight length of $\tau < 5$ mm	31
(4) $\Delta\theta_{\tau \to X} \geq 15$ mrad	28
(5) Pair charm: 0.1 mm $\leq$ flight length < 5 mm (charged decays with $\Delta\theta \geq 15$ mrad or neutral decays)	20

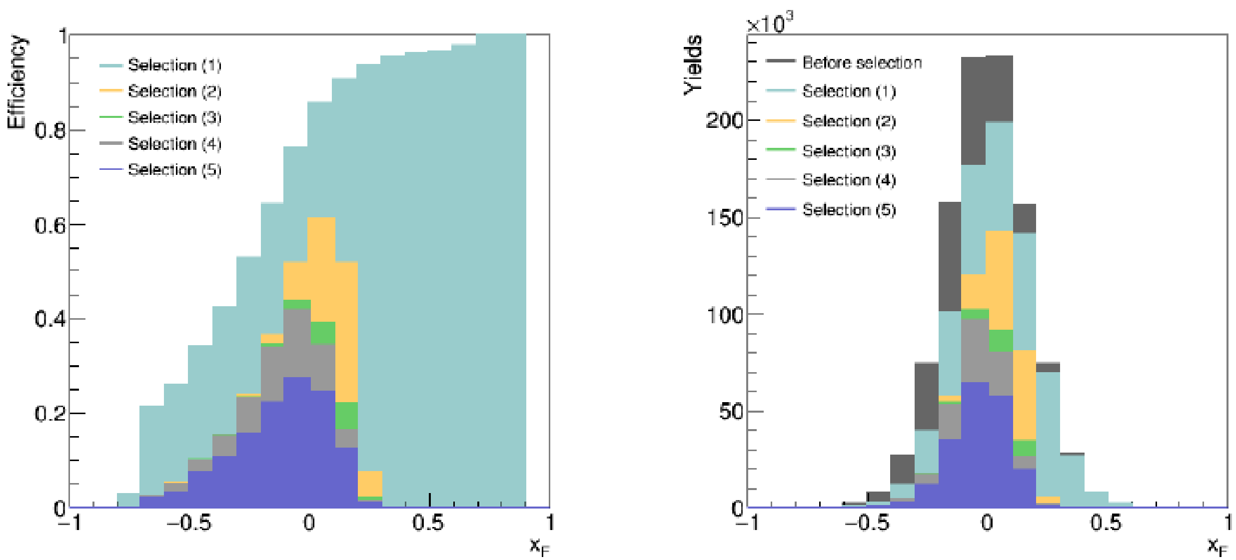


Figure 7: The estimated detection efficiency as a function of x_F (left) and the x_F distributions after the selection (right). Selection (1)-(5) are described in the text.

Remark :: Larger efficiency for large XF for other charm,
because no strict selection (2) about small angle kink .